NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

SYSTEMS ENGINEERING CAPSTONE PROJECT REPORT

A METHODOLOGY TO ASSESS THE BENEFIT OF OPERATIONAL OR TACTIC ADJUSTMENTS TO REDUCE MARINE CORPS FUEL CONSUMPTION

by

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December 2015

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704–0188*

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** December 2015	**3. REPORT TYPE AND DATES COVERED** Capstone Project Report

4. TITLE AND SUBTITLE A METHODOLOGY TO ASSESS THE BENEFIT OF OPERATIONAL OR TACTIC ADJUSTMENTS TO REDUCE MARINE CORPS FUEL CONSUMPTION	**5. FUNDING NUMBERS**
6. AUTHOR(S) Systems Engineering Cohort 311-142M/ Team E2O	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ____N/A____.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited	**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

The United States Marine Corps is too dependent on fossil fuel, which leaves logistics fuel support and supply lines vulnerable to attack, potentially degrading Marine Corps capabilities and ultimately putting Marines at risk. A need exists to identify doctrine, organization, training, materiel, leadership and education, personnel, and facilities (DOTMLPF) changes that provide a positive impact on energy efficiency while maintaining or improving operational effectiveness, essentially improving operational reach. Using the systems engineering process, key capabilities were identified from the Expeditionary Energy Office (E2O) stakeholders and used to develop a methodology to assess potential improvements to operational reach in the context of a Marine Expeditionary Unit (MEU) operation. At the heart of the methodology was a discrete event model developed to simulate the conditions of a close air support (CAS) operation and ground combat support (GCS) operation. Using a specific ship-to-shore vignette, factors were identified and a design of experiments (DOE) analysis was conducted to assess changes to doctrine, aircraft materiel solution, and environmental conditions on operational reach. This report: a) demonstrates the methodology developed, b) identifies the effects of the factors on extending the operational reach of a CAS and GCS operation, and c) recommends future efforts to continue research.

14. SUBJECT TERMS systems engineering, model based systems engineering, fuel consumption, close air support, ground combat support, operational effectiveness, DOTMLPF	**15. NUMBER OF PAGES** 229
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified Distribution A	Unclassified Distribution A	Unclassified Distribution A	UU

NSN 7540–01-280-5500 Standard Form 298 (Rev. 2–89) Prescribed by ANSI Std. 239–18

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A METHODOLOGY TO ASSESS THE BENEFIT OF OPERATIONAL OR TACTIC ADJUSTMENTS TO REDUCE MARINE CORPS FUEL CONSUMPTION

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Submitted in partial fulfillment of the
requirements for the degrees of

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NAVAL POSTGRADUATE SCHOOL
December 2015

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ABSTRACT

The United States Marine Corps is too dependent on fossil fuel, which leaves logistics fuel support and supply lines vulnerable to attack, potentially degrading Marine Corps capabilities and ultimately putting Marines at risk. A need exists to identify doctrine, organization, training, materiel, leadership and education, personnel, and facilities (DOTMLPF) changes that provide a positive impact on energy efficiency while maintaining or improving operational effectiveness, essentially improving operational reach. Using the systems engineering process, key capabilities were identified from the Expeditionary Energy Office (E2O) stakeholders and used to develop a methodology to assess potential improvements to operational reach in the context of a Marine Expeditionary Unit (MEU) operation. At the heart of the methodology was a discrete event model developed to simulate the conditions of a close air support (CAS) operation and ground combat support (GCS) operation. Using a specific ship-to-shore vignette, factors were identified and a design of experiments (DOE) analysis was conducted to assess changes to doctrine, aircraft materiel solution, and environmental conditions on operational reach. This report a) demonstrates the methodology developed, b) identifies the effects of the factors on extending the operational reach of a CAS and GCS operation, and c) recommends future efforts to continue research.

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LIST OF ACRONYMS AND ABBREVIATIONS

ABMS	agent based modeling and simulation
ACE	air combat element
AH-1Z	Super Cobra
APKWS	advanced precision kill weapons system
APU	auxiliary power unit
AV-8B	Harrier
C2	command and control
C&A	certification and accreditation
CAS	close air support
CASEVAC	casualty evacuation
CD&I	Combat Development and Integration
CH-53K	King Stallion
CI	configuration item
CMC	Commandant of the Marine Corps
CONOP	concept of operations
DES	discrete event simulation
DOD	Department of Defense
DOE	design of experiments
DOTMLPF	doctrine, organization, training, materiel, leadership and education, personnel, and facilities
DR	disaster relief
E2O	Expeditionary Energy Office
E2W2	Expeditionary Energy, Water, and Waste
EFSS	Expeditionary Fire Support System
EPA	Environmental Protection Agency
EW14	Expeditionary Warrior 2014
F-35B	Joint Strike Fighter
FAC(A)	Forward Air Controller - Airborne
FFBD	functional flow block diagram
FHA/DR	foreign humanitarian aid / disaster relief

FO	forward observer
FOM	figure of merit
FSU	former soviet union
GCE	ground combat element
GCS	ground combat support
GPMD	gallons per Marine per day
I/O	input / output
ICD	initial capabilities document
IPR	in-process review
IPT	integrated product team
IT-LSV	Internally Transportable – Light Strike Vehicle
JTAC	Joint Terminal Attack Controller
KC-130J	Marine Super Hercules
LCAC	Landing Craft Air Cushion
LER	loss exchange ratio
LHD	Landing Helicopter Dock
LPD	Landing Platform/dock
LSD	Landing Ship Dock
LWPS	lightweight water purification system
M&S	modeling and simulation
M777A2	howitzer
MAGTF	Marine Air-Ground Task Force
MANA	Map Aware Non-Uniform Automata
MCWL	Marine Corps Warfighting Lab
MEB	Marine Expeditionary Brigade
MEU	Marine Expeditionary Unit
MOE	measure of effectiveness
MOP	measure of performance
MTVR	Medium Tactical Vehicle Replacement
MV-22B	Osprey
NATOPS	Naval Air Training and Operating Procedures Standardization

NPS	Naval Postgraduate School
OFOM	overall figure of merit
OMOE	overall measure of effectiveness
ONR	Office of Naval Research
Pd	probability of desired effect
PEOO	Program Executive Officer
PERM	Precision Extended Range Munition
QRF	quick reaction force
ROI	return on investment
S&T	science and technology
SA	situational awareness
SE	systems engineering
STTO	start, taxi and take-off
TECOM	Training and Education Command
TTP	tactics, techniques, and procedures
TWPS	tactical water purification system
SPMAGTF	Special Purpose Marine Air Ground Task Force
UH-1Y	Huey
USMC	United States Marine Corps
WTI	Weapons and Tactics Instructor

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EXECUTIVE SUMMARY

The Marine Corps "requires an expeditionary mindset focused towards increased efficiency and reduced fuel consumption" while maintaining mission success (*USMC Expeditionary Energy Strategy and Implementation Plan* 2011). The basic problem is that the Marine Corps is too dependent on fossil fuel and that a change in the overall energy strategy is required in order for the Marine Corps to operate lighter and faster, while maintaining its lethal edge. A need exists to identify doctrine, organization, training, materiel, leadership and education, personnel, and facilities (DOTMLPF) changes that provide a positive impact on energy efficiency while maintaining or improving operational effectiveness, essentially improving operational reach (*USMC Expeditionary Energy Strategy and Implementation Plan* 2011).

A systems engineering process was used to identify key capabilities from the Expeditionary Energy Office (E2O) stakeholders and used to develop a methodology to assess potential improvements to operational reach in the context of a Marine Expeditionary Unit (MEU) operation. Based on the capability needed, the initial system model was identified as a specific set of Marine Corps military systems operating in the context of an MEU. The model and methodology developed would, in the context of an MEU, provide tactics and techniques that enhanced fuel efficiency while maintaining operational effectiveness or maintained existing fuel usage while improving operational effectiveness. The MEU system model included ship-to-shore and return movements, close air support (CAS) maneuvers, and ground combat support (GCS) maneuvers. Not only were tactics and operations varied within the model of the MEU, but also changes to hardware systems were varied in the model such as indirect fire weapon systems, air and ground systems, and potentially new hardware currently in development. The mission was to conduct the operational concept shown in Figure 1.

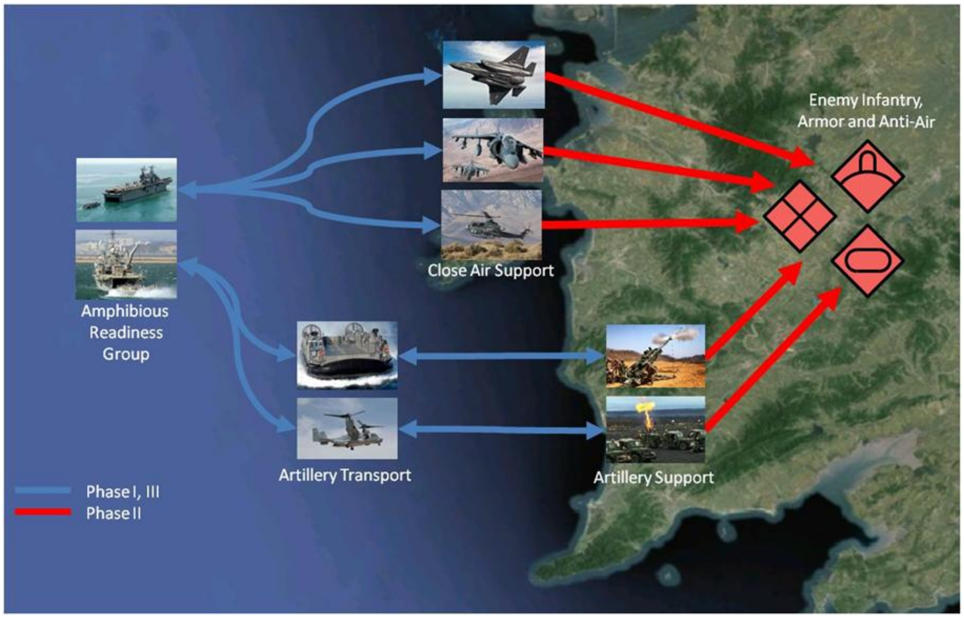

Figure 1. MEU Operational Concept Model for Simulation

To address the problem, potential DOTMLPF solutions to reduce fuel consumption while maintaining or improving operational effectiveness during a close air support and ground combat support model were developed. These specific ship-to-shore engagement scenarios using close air support (CAS) and ground combat support (GCS) were chosen based on E2O needs, stakeholder feedback, and the experience of the team. Each model was developed to simulate ship-to-shore transit, battle engagement, and return-to-ship transit. Factors were varied in each model to simulate DOTMLPF changes in order to determine the effects on fuel consumption and operational effectiveness during each mission. The scenarios for this project build from recommended works from the 2014 capstone project (Bennett et al. 2014) of modeling an end to end engagement. To better understand how energy is consumed during air and land engagement both a close air support (CAS) and ground combat support (GCS) model were developed.

An analysis of the MEU was performed in order to identify the functional and physical architectures using MCO 3500.26 (2015) and MCO 3500.99 (2012). A summary of the functional and physical analysis is shown in Table 1.

Table 1. MEU Functional Analysis

Function	Measure of Effectiveness (MOE)	Measure of Performance (MOP)	Assets
1.1 Conduct Assault Support	MOE 1: Percentage of mission window covered	MOP 1: Fuel consumption MOP 2: Length of mission window (time)	MV-22B Osprey, CH-53K King Stallion, KC-130J Marine Super Hercules, AH-1Z Super Cobra, UH-1Y Huey, Landing Craft Air Cushion (LCAC)
1.2.1 Conduct Close Air Support	MOE 2: Percentage of blue forces lost MOE 3: Percentage of targets neutralized	MOP 3: Length of mission (time) MOP 4: Number of targets neutralized MOP 5: Number of blue force assets destroyed	AV-8B Harrier, F-35B Joint Strike Fighter
1.3.1 Conduct Indirect Fires	MOE 4: Percentage of blue forces lost MOE 5: Percentage of targets neutralized	MOP 6: Length of mission (time) MOP 7: Number of targets neutralized MOP 8: Number of blue force assets destroyed	M777A2 howitzer, Expeditionary Fire Support System (EFSS), Medium Tactical Vehicle Replacement (MTVR), Internally Transportable – Light Strike Vehicle (IT-LSV)

At the heart of the methodology was a discrete event model developed to simulate the conditions of a specific ship-to-shore CAS and GCS vignette. For the CAS vignette there were nine independent variables, or factors: environmental variables (temperature, sea state and cloud cover, red force threat level), blue force asset type (Aircraft Type), number of total assets per type (Total Asset Qty), number of assets per launch (Assets per Launch), distance to shore (Ship2Shore Dist), weapon loadout (Loadout). For the GCS vignette there were ten independent variables, or factors: environmental variables (temperature, sea state and red force threat level), type of artillery asset (Weapon Type), weapon loadout (Loadout), total quantity of weapons (Total Weapons Qty), transit medium (Transit Medium), quantity of transit mediums per launch (Transit Medium per Launch), distance to shore (Ship2Shore Dist), and shore to firing position distance (Shore2FirePos Dist). The independent variables provided the necessary data to conduct a

custom design of experiments (DOE) analysis. Operational effectiveness remained a primary consideration during analysis and utilized several measures to quantify mission success.

Given the above independent variables, achieving operational effectiveness or mission success had to be defined for each of the models. Operational effectiveness was defined by four measures: targets neutralized, blue force casualties, mission time, and successful mission. When the CAS and GCS model results were compared, it was found that the CAS model demonstrated significantly greater operational effectiveness in all four metrics than the GCS model. The disparity was based primarily on factors such as target types favorable to air assets, assumptions regarding blue force air superiority, and transit time deviation between sea and air movement to the objective area. The fourth measure encompasses the overarching deviation between the models for defining mission success based on contemplated target sets that remained consistent between models for comparison analysis, but do not necessarily provide the correct weapon to target match.

A custom DOE analysis was conducted to assess how potential changes to variables related to doctrine, materiel solution, and environmental conditions affect or influence operational reach in terms of specific measures of performance (MOP). Using the DOE approach, models were developed for each MOP and the resulting factors assessed in terms of their relative impact to the MOP model prediction. For the CAS scenario, the analysis indicated that the factors distance to shore and number of assets per type had the largest effect on the total fuel used (MOP1) for the MEU operation. The factors number of assets per launch and number of assets per type had the largest effect on the average mission time (MOP2&3) for the MEU operation. The interaction of the factor sea state and number of assets per launch had the largest effect on the percent of targets neutralized (MOP4) for the MEU operation. The interaction of the factor weather and threat level had the largest effect on the percentage of blue force assets destroyed (MOP5) for the MEU operation. The interaction of the factor number of assets per type and the factor threat level had the largest impact on the metric mission success for the MEU operation. Similarly for the GCS scenario, the analysis indicated that the factors transit medium and total weapons quantity had the largest effect on the total fuel used

(MOP1) for the MEU operation. The factors distance to shore and total weapons quantity had the largest effect on the average mission time (MOP2&3) for the MEU operation. The factors threat level and total weapons quantity had the largest effect on the percentage of targets neutralized (MOP7) as well as the percentage of blue force assets destroyed (MOP8) for the MEU operation. The factors total weapons quantity and threat level had the largest impact on the metric mission success for the MEU operation.

Each factor was then converted to a figure of merit (FOM) and ranked in terms of its relative impact to the MOP model prediction. Since the primary focus was on fuel usage and its relative impact on mission success, the FOM for each factor from the total fuel used (MOP 1) model was compared to the FOM for each corresponding factor from the mission success model. The resulting comparison, shown in Figure 2 for the CAS scenario, provided an efficient frontier plot from which to identify the dominant combination of mission success and total fuel used factors. As shown for the CAS scenario, the dominant factor for both the total fuel used MOP1 and mission success was the interaction of the factor number of assets per type at 115% of current doctrine and the factor number of assets per launch at 150% of current doctrine. The effect of the interaction associated with the number of assets per launch at 150% of current doctrine was evident by the minor reduction in mission success, but substantial improvement in total fuel used. The basis for this improvement was essentially the overmatch provided by increased number of assets against the threat, effectively reducing the amount of time burning fuel while trying to defeat the enemy.

A similar approach was used for the GCS scenario, producing an efficient frontier plot that indicated that the interaction of the factor weapon type M777A2 and the factor transit medium by air was the dominant combination for both the total fuel used MOP1 and mission success. For a similar reason, the interaction of the weapon type and the transit medium by air was the dominant combination, primarily based on the shorter mission time which resulted in less fuel usage. In general, the interaction of the factors that significantly impacted (reduced) mission time were also more likely to be part of a combination close to the efficient frontier line.

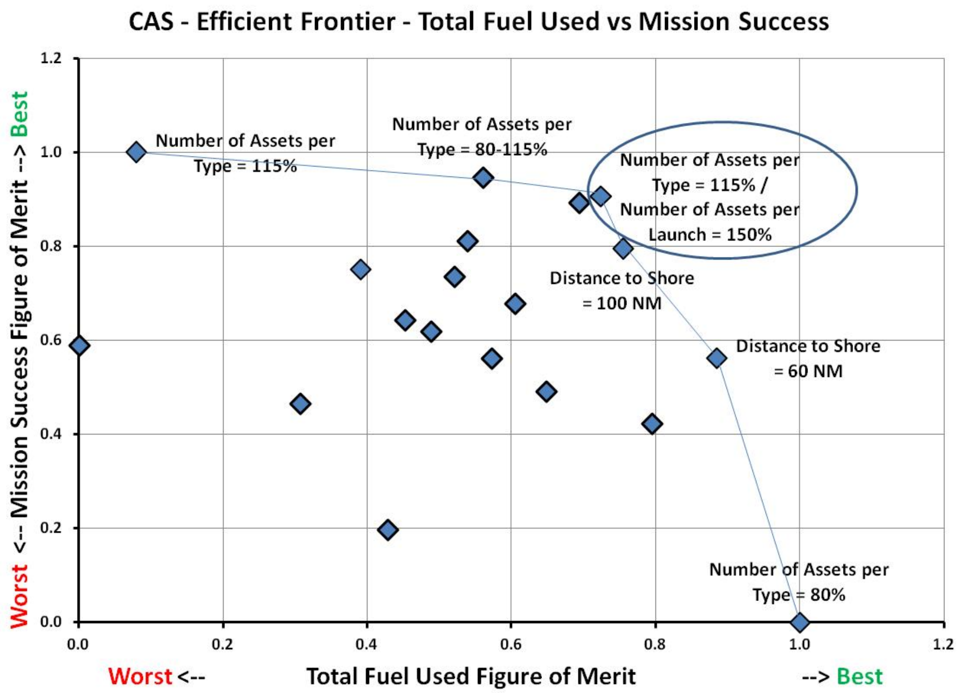

Figure 2. CAS — FOM Efficient Frontier — Total Fuel Used vs. Mission Success

Having identified the dominant combination of factors for both total fuel used and mission success, an analysis was conducted to predict the total fuel used and resulting mission success that would occur due to changes in either doctrine or materiel used during the MEU operation. For the CAS scenario, the dominant combination of factors was used to assess total fuel used and mission success as a result of increasing the number of assets launched to 150% of current doctrine (doctrine change) and the distance to shore (doctrine change). As shown in Figure 3, significant improvement in mission success could be achieved by increasing the number of assets per type to 115% of current doctrine. For distances to shore of 60 NM and 100 NM, significant increases in mission success were predicted with a resulting increase in total fuel used of 20% and 30%, respectively. However, at 300 NM, the increase in mission success was relatively minor even though the increase in total fuel used was still 30%.

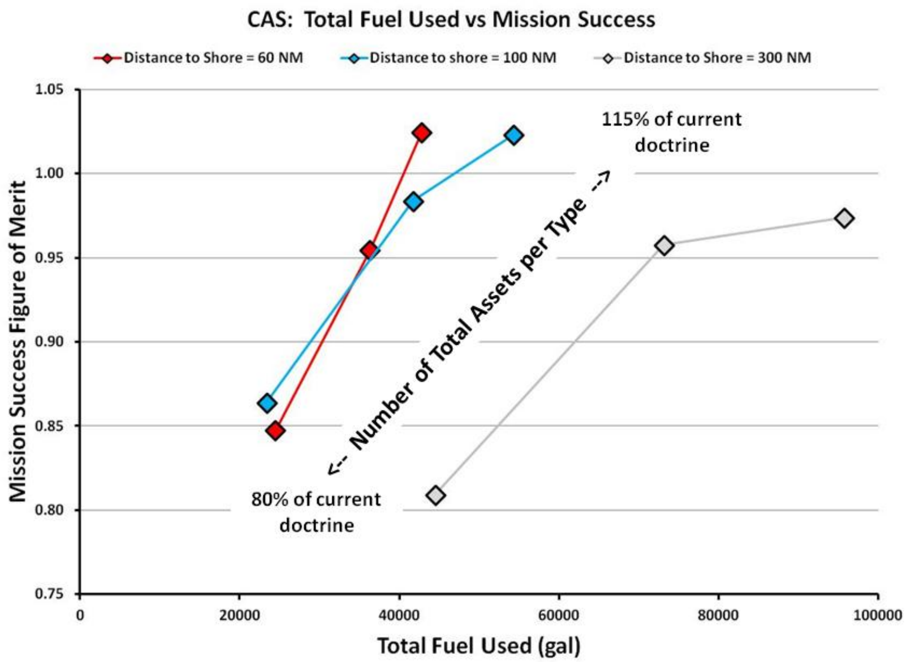

Figure 3. CAS — Total Fuel Used vs. Mission Success: Using Number of Assets Launched = 50% of Current Doctrine

For the GCS scenario, the dominant combination of factors was used to assess total fuel used and mission success as a result of changing the weapon type (materiel solution) and distance to shore (doctrine change) while transiting by air. As shown in Figure 4, for each weapon type, increases in the distance to shore resulted in modest increases (generally 20%) in total fuel used with generally less than a 10% decrease in mission success. Also shown was that increasing the quantity of transit mediums per launch to a value of nine significantly increased mission success while generating the lowest total fuel used for each combination of weapon type and distance to shore. More importantly was the effect of the use of the weapon type M777A2, which provided the best mission success at the least amount of total fuel used, regardless of distance to shore and quantity of transit mediums per launch.

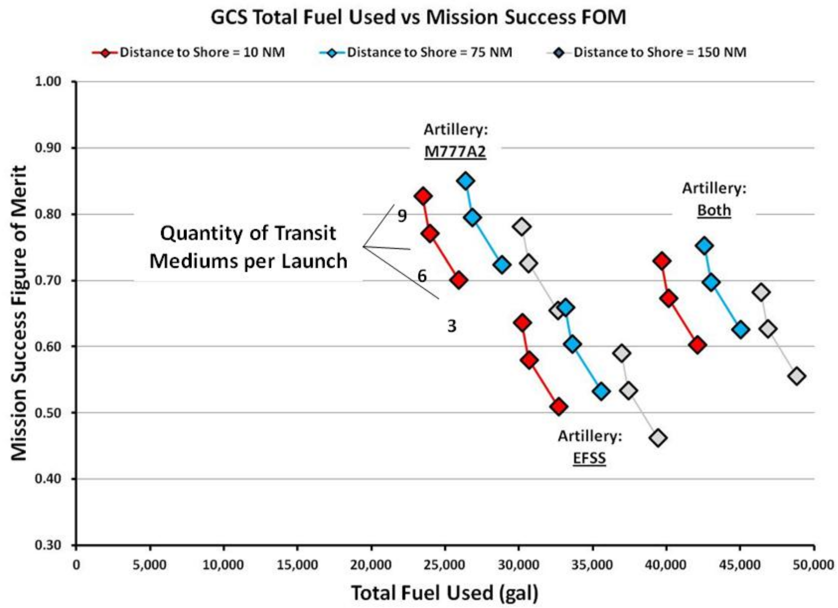

Figure 4. GCS — Total Fuel Used vs. Mission Success: Using Air Transit Medium

Recommended adjustments in doctrine and materiel were extracted from this research, and current tactics were validated. Additional research, preferably at the classified level, would add fidelity to the fuel consumption and mission success results of a CAS and GCS operational scenario. Additional research using models for a QRF, combined CAS and GCS scenario, and for an evolving threat are recommended future efforts.

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I. INTRODUCTION

A. BACKGROUND

Now more than ever, the operating environment of the United States Marine Corps (USMC) “requires an expeditionary mindset geared toward increased efficiency and reduced fuel consumption” (*United States Marine Corps Expeditionary Energy Strategy and Implementation Plan* 2010). This transformation, guided by numerous operational energy efficiency initiatives, “is essential to rebalance [the] Corps and prepare it for the future” (*USMC Expeditionary Energy Strategy and Implementation Plan* 2011c). One of the approaches planned by the Marine Corps is to partner with academia to assist with implementation of their initiative “develop and adopt technology” (*USMC Expeditionary Energy Strategy and Implementation Plan* 2011c). Working with the USMC Expeditionary Energy Office (E2O), the project team conducted a systems engineering analysis to support the larger goal of the Marine Corps to improve overall fuel efficiency.

B. PROJECT PURPOSE

The primary purpose was to develop a methodology to assess the benefit of energy efficiency initiatives to reduce Marine Corps fuel consumption. The methodology was developed utilizing a robust systems engineering (SE) process and resulted in a simulation model that has the ability to predict potential energy efficiency improvements from changes to a portion of the Marine Corps’ doctrine, organization, training, materiel, leadership and education, personnel, and facilities (DOTMLPF) approach to problems, specifically doctrine and materiel solutions.

In addition to the methodology, the project team also needed to identify metrics that could be used to quantitatively assess the fuel usage associated with an efficiency initiative. These metrics needed to capture true fuel usage and be less sensitive to variations in operational scenarios and the systems within they operated. Metric data should provide unique insight to further support the development of Marine Corps initiatives to advance metering and monitoring initiatives.

As part of the development of the operational scenario and battle engagement vignettes, the project team also needed to develop realistic performance attributes for several existing and future Marine Corps platforms. Performance information developed for the various platforms and systems would further advance other modeling and simulations efforts supporting the larger Marine Corps goal of improving overall fuel efficiency.

C. PROBLEM SUMMARY

The Marine Corps usage of fuel continues to increase with the rise of energy consuming assets on the battlefield. Supply lines added to support this dependency are vulnerable to attack, potentially degrading Marine Corps capabilities and putting Marines at risk. The Marine Corps "requires an expeditionary mindset geared toward increased efficiency and reduced [fuel] consumption" (*United States Marine Corps Expeditionary Energy Strategy and Implementation Plan* 2011c) while maintaining mission success. The basic problem is that the Marine Corps is too dependent on fossil fuel and that a major change in overall energy strategy is required in order for the Marine Corps to operate lighter and faster, while maintaining its lethal edge.

D. BENEFIT OF STUDY

This study identified specific DOTMLPF areas that when adjusted provided fuel usage improvements while maintaining operational effectiveness. A ship-to-shore scenario comprising of staging, transport of assets, engagement, and return to ship was analyzed through the development and modeling of vignettes with scenario factors varied to identify the impact on fuel usage. A ship-to-shore operational scenario focused our efforts on modeling a Marine Expeditionary Unit (MEU) as the system. Independent factors were identified and adjusted in a discrete event simulation of a ship-to-shore operation in order to identify any fuel usage improvements without compromising operational effectiveness. Applying universal fuel usage metric(s) facilitated a cross-comparison between factors when specific DOTMLPF areas of ship-to-shore were adjusted. Future efforts will be able to add fidelity to the factors that are seen to give the

greatest improvement in fuel usage and to identify improvements in other operational scenarios.

Requiring large quantities of fuel to complete operational missions puts the USMC and the Department of Defense (DOD) at risk mission success if an enemy targets the force's fuel supply. Decreasing the dependence on fossil fuels while deployed without sacrificing operational effectiveness would lower the risk of this vulnerability occurring and creating severe consequences.

E. APPROACH

This section describes the SE approach from problem definition to validation of the system. It also describes the stakeholders involved, the constraints and assumptions.

1. Systems Engineering Process

There are many definitions of the SE process, but in simple terms it can be defined as a disciplined approach used to transform an operational need into a successful system or tangible product. One of the more common descriptions of the SE process comes from Forsberg and Mooz (1992) who describe the SE process using a Vee. The Forsberg and Mooz systems engineering Vee, shown in Figure 1, describes the SE process as "a decomposition and definition flow down the left side of the Vee and an integration and verification flow up the right side of the Vee" (Forsberg and Mooz 1992). The left side of the Vee starts with the steps necessary to understand the user's requirement and to develop a system concept and validation plan. Additional decomposition then produces the system performance specification and the system validation plan. These documents are further decomposed into design-to specifications and verification plans for specific configuration items (CIs) that make up the system. Final decomposition results in the development of build-to specifications and inspection plans for each CI, which are used to actually fabricate or code CIs. The flow up the right side of the Vee begins with the verification or inspection of the CIs as defined in the build-to documentation. Further integration is performed to assemble the CIs into subsystems or systems and to verify their performance against the corresponding design-to specifications. Next, integration is performed to complete the system and verification

of the system performed against the top-level system performance specification. Finally, the system is validated using the user validation plan, ensuring the requirements and capabilities originally defined by the stakeholders are achieved. As with the SE process, the ultimate goal of the Forsberg and Mooz Vee is to guide the development of a successful system or tangible product.

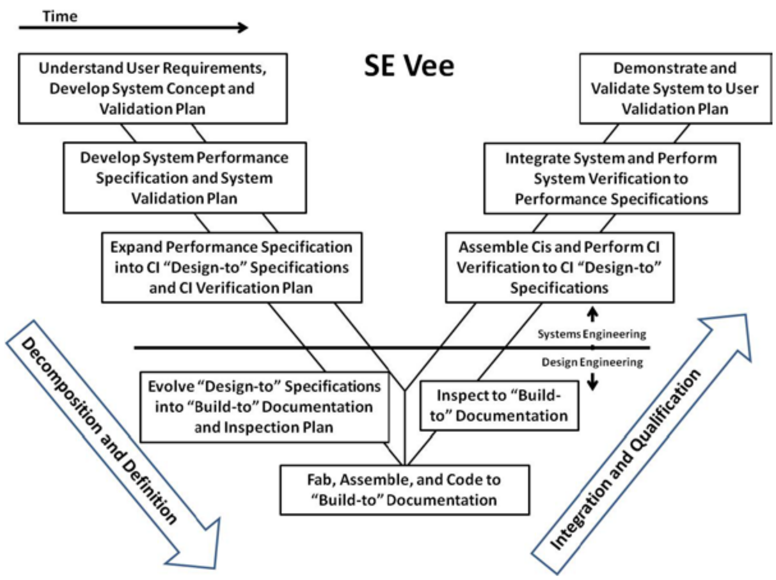

Figure 1. Systems Engineering Vee (adapted from Forsberg and Mooz 1992)

For this study, the SE process was a tailored version of the Forsberg and Mooz Vee. This tailored-SE Vee, shown in Figure 2, was similar to the Forsberg and Mooz Vee and contained a series of decomposition steps that flowed down the left side of the SE Vee and a series of integration and verification steps that flowed up the right side. The individual steps followed in this tailored-SE Vee are described as follows.

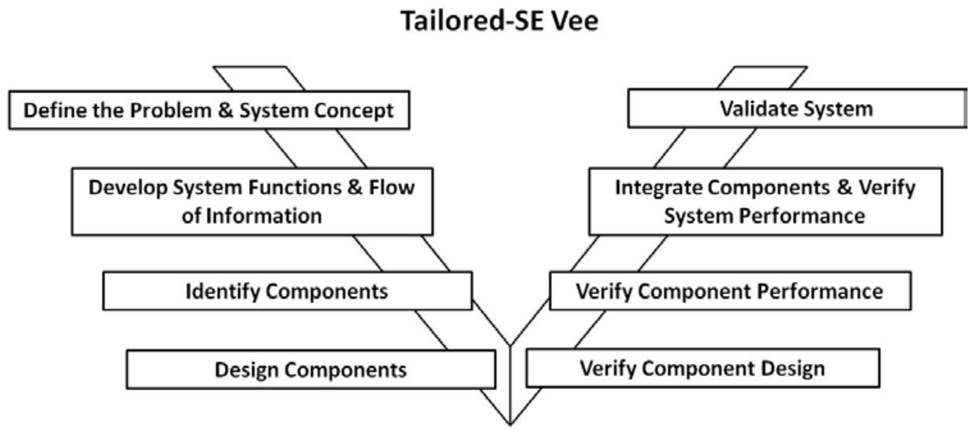

Figure 2. Tailored-SE Vee (adapted from Forsberg & Mooz 1992)

a. Step One: Define the Problem and System Concept

The first step of the tailored-SE Vee focused on defining the problem and development of an initial system concept. The functions completed in this first step were: a) identify the problem, b) identify the capability needed, c) develop an operational concept, d) identify the system boundary with external systems, e) develop system input/ output diagram, and f) develop operational vignettes. Qualification requirements define the approach necessary to confirm both the success of the system and satisfaction of the stakeholders. The capability needed was identified by conducting a need/gap analysis that consisted of the following functions: a) identify primitive need, b) conduct stakeholder analysis, c) conduct literature search, and d) identify effective need. The results obtained from step one were documented as the system design problem and used as input to step two of the tailored-SE Vee.

b. Step Two: Develop System Functions and Flow of Information

The second step of the tailored-SE Vee focused on developing a hierarchical model of the functions performed by the system and the tracing of information flow both inside and external to the system. The functions completed in this second step were: a) develop hierarchical model of system functions, b) develop system functional flow block diagram, c) develop a hierarchy of system functions, d) develop Measures of Effectiveness (MOE) and Measures of Performance (MOP), e) develop a set of

originating requirements (including qualification requirements) for the system, f) trace originating requirements and MOEs/MOPs to appropriate system functions, and g) identify a set of qualification requirements to be used to verify the performance of the system. The results obtained from step two were documented as the system functional architecture and used as input to step three of the tailored-SE Vee.

c. Step Three: Identify Components

The third step of the tailored-SE Vee focused on identifying the components of the system without any specification of their performance, i.e., just a generic description. Starting with the functional architecture previously developed, generic components of the system were identified for each function. In addition, qualification requirements were also identified in order to verify component performance. The results obtained from step three were documented as the system generic physical architecture.

d. Step Four: Design Components

The fourth step and last step of the decomposition phase down the left side of the tailored-SE Vee focused on developing a specific design for each generic component of the system. Starting with the generic physical architecture previously developed, specific designs where identified for each function and corresponding generic component. Design information such as specific fuel usage metric, specific vehicle and weapon system, and detailed engagement tactic were defined in this step. Qualification requirements for each design were also identified in order to verify specific design requirements. The results obtained from step four were documented as the system instantiated physical architecture.

e. Step Five: Verify Component Design

The fifth step started the integration and qualification flow up the right side of the tailored-SE Vee and included the steps necessary to verify the components and system developed during the decomposition phase. In the fifth step, individual components developed from the previous step were verified to ensure compliance with the design requirements identified in step four. The output from this step was the verified

instantiated physical architecture and a summary assessment of how well each component met its design requirement.

f. Step Six: Verify Component Performance

In step six of the tailored-SE Vee, each component was verified to ensure compliance with the performance requirements identified in step three. The output from this step was the verified generic physical architecture and a summary assessment of how well each component met its required performance.

g. Step Seven: Integrate Components and Verify System Performance

In step seven of the tailored-SE Vee, individual components were integrated into a single system and the system verified to ensure compliance with system level performance requirements identified in step two. The output from this step was the verified functional architecture and a summary assessment of how well the system met its required performance.

h. Step Eight: Validate System

The eighth step and last step of the tailored-SE Vee focused on validating the system developed. In this last step, performance of the system was validated to ensure that operation of the system provided the capability and results originally required by the stakeholders. The output from this step was the system operational architecture documenting the verified and validated system developed.

2. Project Constraints

A group of six MSSE and MSES distance learning students from the Naval Postgraduate School (NPS) conducted this research and analysis effort over a nine-month period as part of the NPS SE graduation requirements. This study was conducted within the following environment and under the following constraints:

- The study must meet all graduation requirements by December 2015.
- The study must be conducted and completed at an unclassified level.

- Detailed performance parameters (i.e., probability of detection, probability of hit, probability of kill, etc.) are not available for use within the study as these values are classified.
- No funding has been provided for this study.

3. Project Assumptions

To complete this capstone project several assumptions were made:

- Stakeholders will participate in the project development to ensure user needs are being met.
- Enough information for the modeling and simulation of the operational scenarios will be available to perform the project at the unclassified level.
- The right skill set is provided by the team to accomplish the project tasks within the graduation schedule.

4. Stakeholder Analysis

The stakeholders involved with this project include Marine Corps users, operators and maintainers, the Marine Corps Expeditionary Energy Office, the Marine Corps Program Executive Officer (PEO) Land Systems, the Office of Naval Research (ONR), the Capability Development Directorate, Training and Education Command, and the Marine Corps Warfighting Lab. The interests and missions of each of these stakeholders were critical to finding the right solution to the right problem. The high level operational concept and battle engagement scenario were developed in close concert with the actual Marine Corps users, operators and maintainers to ensure a valid model was being developed. The Marine Corps Warfighting Lab (MCWL) assisted by aligning the proper tactics, techniques and procedures with operational concept and battle engagement scenario. These tactics, techniques and procedures were used to develop the baseline model for which fuel consumption and operational effectiveness changes were compared against when DOTMLPF areas were adjusted. As sponsors, the Marine Corps Expeditionary Energy Office (E2O) and Combat Development and Integration (CD&I) define initiatives and requirements in order to maximize the expeditionary capabilities across warfighting functions while minimizing energy use. Their input identified a knowledge gap of understanding the effect of DOTMLPF changes in specific battle engagements. Feedback was continuously received during in-process reviews (IPRs) to ensure the knowledge gained from this project benefited the needs of E2O and CD&I.

The stakeholder analysis was important to capture the needs of various users and Marine Corps leadership to see the problem area from multiple perspectives. Stakeholder involvement identified a primitive need of learning what changes to DOTMLPF would provide a positive impact on energy efficiency while maintaining or improving operational effectiveness.

The primary stakeholders have been identified in Table 1. Stakeholders are listed in order of precedence with their focused area of interest described in the third column. Having an order of precedence among the stakeholders allowed for need prioritization in case of conflicting interests, or more interests than could be accomplished in this project.

Table 1. Stakeholder Analysis

Priority	Stakeholder	Type	Interest
1	Marine Corps Users, Operators, Maintainers	User	Maintain combat effectiveness while reducing energy consumption/logistics burden.
2	Marine Corps Expeditionary Energy Office (E2O)	Sponsor	Analyze, develop, and direct the Marine Corps' energy strategy to optimize expeditionary capabilities across warfighting functions.
3	Marine Corps PEO Land Systems	Decision Maker	Acquisition of implementation of Marine Corps initiatives that produce tangible improvements to energy efficiency.
4	Office of Naval Research (ONR)	Decision Maker	Explore science and technology (S&T) objectives that relate to expeditionary energy as called out in 2012 Marine Corps S&T Strategic Plan.
5	Combat Development and Integration (CD&I)	Sponsor	Develop and integrate operationally effective capabilities that meet the needs of the warfighter.
6	Training and Education Command (TECOM)	Decision Maker	Ensure that new energy efficiency technology is quickly and reliably trained.
7	Marine Corps Warfighting Lab (MCWL)	Decision Maker	Identification of new understanding in Tactics, Techniques and Procedures (TTP) through expeditionary operational scenario development.

5. Project Scope

To determine potential DOTMLPF solutions to reducing fuel consumption while maintaining or improving operational effectiveness a close air support and ground combat support model were developed. Specific ship-to-shore engagements using close air support (CAS) and ground combat support (GCS) were chosen based on E2O needs, stakeholder feedback, and the experience of the team. Each model was developed to simulate ship-to-shore transit, battle engagement, and return-to-ship transit. Factors were varied in each model to simulate DOTMLPF changes in order to determine the effects on fuel consumption and operational effectiveness during each mission. As described later in Chapter 2, the scenarios for this project build from recommended works from the 2014 capstone project (Bennett et al. 2014) of modeling an end to end engagement. To better understand how energy is consumed during air and land engagement both a close air support and ground combat support model were developed.

6. Research Questions

From the literature review summarized in chapter two, the stakeholder analysis, and the project being scoped the research questions were determined to be:

- What specific changes of the Marine Corps DOTMLPF could improve fuel usage during a ship-to-shore MEU operation?
- What effect does a change in materiel solution and doctrine during a ship-to-shore operation have? Which factor or combination of factors provides the greatest decrease in fuel usage without sacrificing operational effectiveness?
- Can a discrete event simulation of an MEU ship-to-shore operational scenario to provide close air support capture realistic improvements in fuel usage due to changes in aircraft materiel solution (F-35B versus AV-8B) and doctrine (total asset quantity and assets per launch)?
- Can a discrete event simulation of an MEU ship-to-shore operational scenario to provide artillery support capture realistic improvements in fuel usage due to changes in artillery materiel solution (Expeditionary Fire Support System versus M777A2 howitzer) and doctrine (assets per launch and shore-to-staging distance)?

These research questions helped to scope and define the problem in order to provide a solution.

F. SUMMARY

This chapter outlined the background, problem summary, project benefit, stakeholder input, project constraints, project assumptions, and research questions. The SE approach was described from problem definition to solution validation. The tailored Vee approach was decomposed into eight steps and the results are described in the remaining chapters.

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II. PROBLEM AND SYSTEM CONCEPT

This chapter describes step one of the SE process: problem definition. Once the SE approach was defined a combination of a literature review and stakeholder involvement lead to the definition of the problem. A clear understanding of the problem allowed for the formulation of focused research questions, which are addressed through this report.

A. PROBLEM

Since the Vietnam conflict, there has been a 175% increase in gallons of fuel used per U.S. Marine per day (*United States Marine Corps Expeditionary Energy Strategy and Implementation Plan* 2011). Since 2001, Marine infantry battalions have experienced a 200% increase in the number of vehicles on hand and with the addition of armor protection, a "30% decrease in the fuel mileage across the tactical vehicle fleet" (*DC Installations and Logistics, Life-Cycle Management Branch Requirements Section* 2011a). Today, "the Marine Corps consumes [over] 200,000 gallons of fuel per day in Afghanistan" (*MEF-A REPOL* 2010). "Each of the more than 100 forward operating bases in Afghanistan requires a daily minimum of 300 gallons of diesel fuel" (*GAO Report* 2009). Marine infantry companies use more fuel than infantry battalions did ten years ago (*USMC E2 Strategy and Planning Guidance* 2011).

Logistics support and supply lines added to support this dependency are vulnerable to attack, potentially degrading Marine Corps capabilities and ultimately putting Marines at risk. Now more than ever, the operating environment of the Marine Corps requires an expeditionary mindset geared toward increased efficiency and reduced fuel consumption. This transformation is essential to rebalance the Marine Corps and prepare it for the future (*Commandant's Planning Guidance* 2010). The basic problem is that the Marine Corps is too dependent on fossil fuel and that a major change in overall energy strategy is required in order for the Marine Corps to operate lighter and faster, while maintaining its lethal edge.

B. CAPABILITY NEEDED

1. Primitive Need

To begin the transformation, the Marine Corps developed an expeditionary energy strategy that provided an operational framework of goals to increase combat effectiveness through ethos, energy efficiency, and the use of renewable energy (*USMC E2 Strategy and Implementation Plan* 2011c). As part of this strategy, the Marine Corps identified fourteen energy efficiency initiatives; each initiative is implemented with either a materiel or non-materiel solution.

One of these initiatives, *Train and Educate Our Marines in Expeditionary Energy*, identified the need to optimize energy efficiency and combat (operational) effectiveness. For this initiative, the challenge was to identify changes to DOTMLPF that would generate a positive impact on energy efficiency, while maintaining operational effectiveness. Simply stated, a primitive need of the Marine Corps was the identification of changes to DOTMLPF that would provide a positive impact on energy efficiency while maintaining or improving operational effectiveness.

2. Literature Review and Research

The primary purpose of the literature review was to gain a reasonable understanding of current USMC E2O efforts, identify potential capability gaps currently being experienced by the Marine Corps in the area of energy efficiency, and to guide the formulation of research questions to guide the identification of the research topic. Review of previous Naval Postgraduate School (NPS) capstone projects was conducted to understand the results and recommendations from related assessments previously conducted and to avoid duplication of efforts. The literature review assisted in scoping and defining the problem, which lead to the formulation of the focused research questions.

a. USMC Expeditionary Energy Strategy Implementation Planning Guide

The planning guide communicates the vision and goals of the Commandant of the Marine Corps (CMC) for expeditionary and installations energy. Specific missions and

timeframes are outlined in the plan for decreasing the dependence on fossil fuels in a deployed environment. Fuel usage and cost has increased dramatically over the years with the increase in assets such as radios, computers, and vehicles. One goal outlined within the plan is to “increase the energy efficiency of weapons systems, platforms, vehicles, and equipment” by 50% by 2025 (*USMC E2 Strategy and Implementation Plan* 2011c). Strategies include reducing energy requirements of systems, reducing water consumption, and increasing alternative energy sources. Achieving a 50% reduction in expeditionary fuel usage by 2025 is broken into a phased system achieving milestones in 2015 and 2020. Success in achieving these goals is measured by using the gallons per Marine per day (GPMD) metric. In addition to materiel solutions, the plan identifies a need for training and education in expeditionary energy, instilling accountability, and institutionalizing energy efficiency through the full range of DOTMLPF solutions. The reference provided insights on the gap in knowledge of DOTMLPF adjustments on fuel consumption and operational effectiveness. The reference also identified a key metric currently being used to assess fuel consumption by the Marine Corps: GPMD.

b. Expeditionary Force 21

The document outlines the guidance on how Marines will be organized, trained, and equipped to fulfill missions. The current goal is to provide the right force structure in the right place at the right time; expeditionary force goals will be assessed and revised as needed annually. The guidance defines the role of the Marine Corps, defines expeditionary, the future operating environment, and the approach of the Marine Corps. The guidance states that the Marine Corps will experiment with organizational refinements within the Marine Air-Ground Task Force (MAGTF), adjust forward posture, increase partnership with the Navy, and enhance littoral maneuvering capability (United States Marine Corps 2014). This reference provided insights about how to structure forces within this project’s model to respond within a given scenario. This reference also assisted in defining the system in this project to be an MEU.

c. Expeditionary Warrior 2014

Expeditionary Warrior 2014 (EW14) is the latest iteration in the series of annual Title 10 War games sponsored by the Marine Corps Warfighting Laboratory. The main objective of EW14 is to "examine how an integrated maritime operations center and a regionalized Marine Expeditionary Brigade headquarters can enable the emergent force to address engagement and crisis response requirements" (United States Marine Corps 2014). The study examined the feasibility of and ways to optimize effectiveness of compositing and aggregating various regional forces together in order to fully leverage their respective capabilities and strengths. This resource shaped the lateral limits of the capstone project in order to ensure the wargaming scenarios selected were relevant and obtained the appropriate scope. The resource also highlighted an area of interest being a simulation analysis of the energy footprint of various assets in support of an amphibious raid. The context of the MEU system was determined based on research using this reference and included ship-to-shore movement, Air Combat Element (ACE) maneuvers, and Ground Combat Element (GCE) maneuvers.

d. Initial Capabilities Document for the United States Marine Corps Expeditionary Energy, Water, and Waste

The Initial Capabilities Document (ICD) describes Expeditionary Energy, Water, and Waste (E2W2) capabilities, gaps, and solution approaches across military operations through 2025 (*Initial Capabilities Document for the United States Marine Corps Expeditionary Energy, Water, and Waste* 2011b). The ICD support the CMC vision of being the premier self-sufficient expeditionary force with increased combat effectiveness by identifying 152 gaps that affect energy, water, and waste, which is a starting point for developing solutions (*Initial Capabilities Document for the United States Marine Corps Expeditionary Energy, Water, and Waste* 2011b). The ICD organized the gaps by the top ten capability requirements by gap priority. Some of the top priorities are to "conduct combat operations across the MAGTF with minimal energy and energy related logistics requirements, provide the capability to measure energy, water, and waste resources in an expeditionary environment, [and] plan for reductions in energy demands of current and future capability sets without reducing combat / mission effectiveness" (*Initial*

Capabilities Document for the United States Marine Corps Expeditionary Energy, Water, and Waste 2011b). An assessment of non-materiel approaches was made through a DOTMLPF analysis and solutions to mitigate the capability gaps were identified, and can have the most immediate impact since they can be applied without delay of materiel solution development. However, to completely remove the capability gaps a materiel solution would be needed. This reference provided insights into what already had been explored, what areas could be expanded, and what fuel consumption metrics were most beneficial to indicating energy improvement. This project expanded on the DOTMLPF analysis by modeling energy effects when DOTMLPF areas were adjusted within specific battle engagement scenarios.

e. 2014 Capstone Project (Bennett et al. 2014)

The 2014 capstone project focused on establishing the relationship between energy demand and Marine Expeditionary Brigade (MEB) size in the context of a successful USMC expeditionary mission. Specifically, the 2014 capstone project evaluated operational energy efficiencies associated with force scale alternatives of a Special Purpose Marine Air Ground Task Force (SPMAGTF) unit operating in the West Africa area of responsibility.

The 2014 capstone team recommended future research in holistic mission modeling. The 2014 capstone project scenario focused on a land based engagement, where Marines were transported to the battle sight using the MV-22, CH-53K, or HMMWV. As described in USMC Expeditionary Force 21, the battle space will be well integrated and utilize elements of air, land, and sea effectively to support the dominance of the enemy (United States Marine Corps 2014). If all three elements were modeled as part of the Barra Vignette, a better understanding of how energy is committed and consumed across the MAGTF and how it relates to effectiveness could emerge. The approach in this 2015 capstone report builds from the 2014 recommendation of modeling an end to end engagement. The approach taken is understanding energy demands during ACS and GCS from ship-to-shore, battle, and return. A comprehensive summary of the 2014 report can be found in Appendix A. This reference provided the backbone of our

battle engagement scenario of a ship-to-shore and return engagement. The battle engagement for this project was tailored to focus on adjusting DOTMLPF areas of close air support to gain improvements in energy usage while maintaining operational effectiveness.

f. 2013 Capstone Project (Besser et al. 2013)

The 2013 capstone project focused on reducing the energy demand and operational footprint of an MEU while meeting mission requirements. Specifically, the 2013 project evaluated the impact of ground transportation, water generation and computer systems on fuel usage and MEU footprint in the context of a foreign humanitarian aid / disaster relief (FHA/DR) mission. The primary focus of the 2013 scenario was to evaluate the efficiency tradeoff of delivering water using MEU vehicles versus producing the water onsite with water purification systems. For the 2013 study, the primary MOEs included:

- gallons of fuel consumed
- equipment footprint on naval vessels
- water and supplies delivered
- water required from the Seabase
- man-hours required

The MEU used in the 2013 scenario gave this project a starting point in the functional analysis. The functions identified in the 2013 project were similar to the functions needed in this project. Similarly, some of the MOEs identified were able to be reused in this project and traced to the identified functions. A comprehensive summary of the 2013 report can be found in Appendix A. This reference reinforced the system definition of an MEU in this project because this reference provided effective study results while investigating potential energy savings within an MEU in a different operational scenario.

g. Literature Search Summary

The past capstone projects, as summarized, identify their research and results in the area of fuel usage and operational effectiveness. The remaining resources summarized shaped our problem and scenario development for this capstone project. From the

literature review, it was clear that the "overarching objective [was] to increase our operational energy efficiency on the battlefield by 50 percent and, in doing so, reduce fuel consumed per Marine per day by 50 percent" (*USMC E2 Strategy and Implementation Plan* 2011c). Realization of this overall objective was not expected to occur overnight, but as a phased approach over the next ten years. The challenge now for the Marine Corps was how to implement these initiatives to achieve the overall goal of a 50% reduction in GPMD by the year 2025.

3. Effective Need

Utilizing the results of the literature review and stakeholder analysis, the primitive need was refined to an effective need. The primitive need of the Marine Corps was the identification of changes to DOTMLPF that would provide a positive impact on energy efficiency while maintaining or improving operational effectiveness. Utilizing the results of the literature review and stakeholder analysis, the project team refined this primitive need into an effective need. The effective need of the Marine Corps was the identification of changes to doctrine and materiel solutions, in the context of an MEU performing ship-to-shore CAS or GCS missions, which a) improve fuel usage while maintaining operational effectiveness or b) maintain existing fuel usage but provide increased operational effectiveness.

4. Capability Needed

Given the effective need and the analysis of the capability gaps identified in the literature review, the project team identified the following as the capability needed by the Marine Corps: a specific change or set of changes to current tactics and techniques associated with an MEU operation that a) provide improved fuel usage while maintaining operational effectiveness or b) maintain existing fuel usage but provide increased operational effectiveness.

C. OPERATIONAL CONCEPT

According to Buede, the "operational concept is a vision of what the system is, a statement of mission requirements, and a description of how the system will be used"

(Buede 2000). The following describes the initial vision and further refinement of the vision for the system selected.

Based on the capability needed, the initial system was identified as a specific set of Marine Corps military platforms and personnel operating in the context of an MEU. The system developed would, in the context of an MEU, provide tactics and techniques that enhanced fuel efficiency while maintaining operational effectiveness or maintained existing fuel usage while improving operational effectiveness. The context of the MEU was determined based on a literature review of Expeditionary Warrior 2014 *(Expeditionary Warrior* 2014b*)*. The MEU system included ship-to-shore and return movements, CAS maneuvers, and GCS maneuvers. Not only were tactics and operations varied within the MEU, but also changes to hardware systems were varied such as indirect fire weapon systems, air and ground systems, and potentially new hardware currently in development. A description of the broad picture of the operational concept is shown in Figure 3.

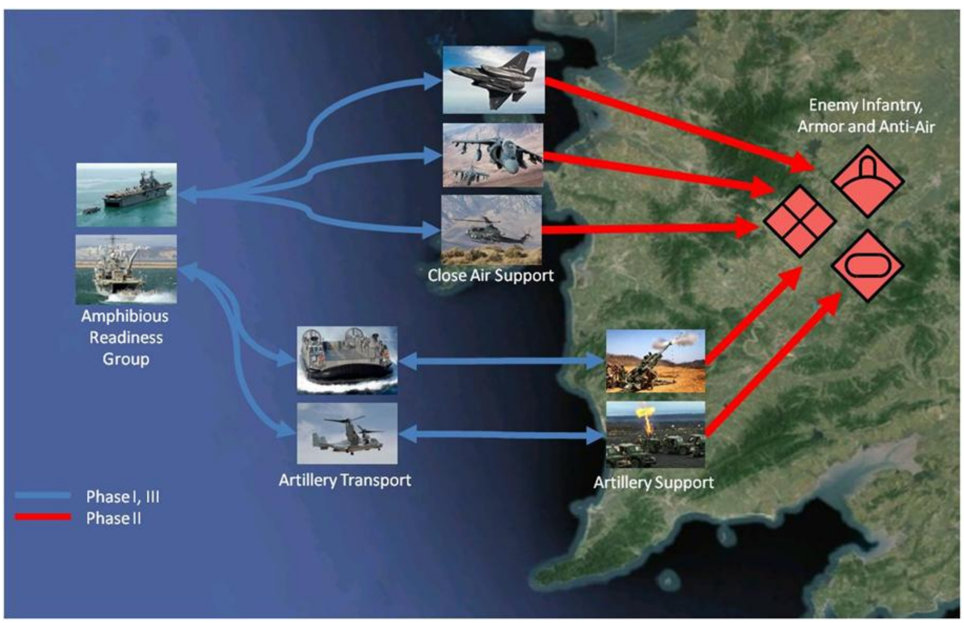

Figure 3. Operational Concept View

As shown, both a CAS and GCS maneuver was selected for the system, which consisted of three operational modes. The ship-to-shore operational mode included those operations necessary to maneuver to and from the sea to a staging area. Engagement operations included those operations necessary to maneuver to and from the staging area to the enemy. Based on feedback from stakeholders, this initial vision of the system was simplified by decoupling the CAS maneuver from the GCS maneuver and treating them as separate system elements. By varying the typical tactics, operations, indirect fire weapon systems, and various air and ground systems associated with this MEU construct, both operational effectiveness and associated fuel usage could be assessed and used to provide stakeholders with recommended changes to DOTMLPF areas.

D. INPUT / OUTPUT MODEL WITH SYSTEM BOUNDARY

According to Blanchard and Fabrycky, "it is important to define the system under consideration by specifying its limits, boundaries, or scope" (Blanchard and Fabrycky 2011). An Input / Output model was developed and input and output information defined to help scope and bound the overall problem. For this project, the initial system was identified as a specific set of Marine Corps military systems operating in the context of an MEU. The system developed and delivered to the stakeholder represented the best combination of fuel usage and operational effectiveness. As shown in Figure 4, input information passed into the system was defined to be aircraft and vehicle performance, weapon system lethality, and vignette and battle engagement logic.

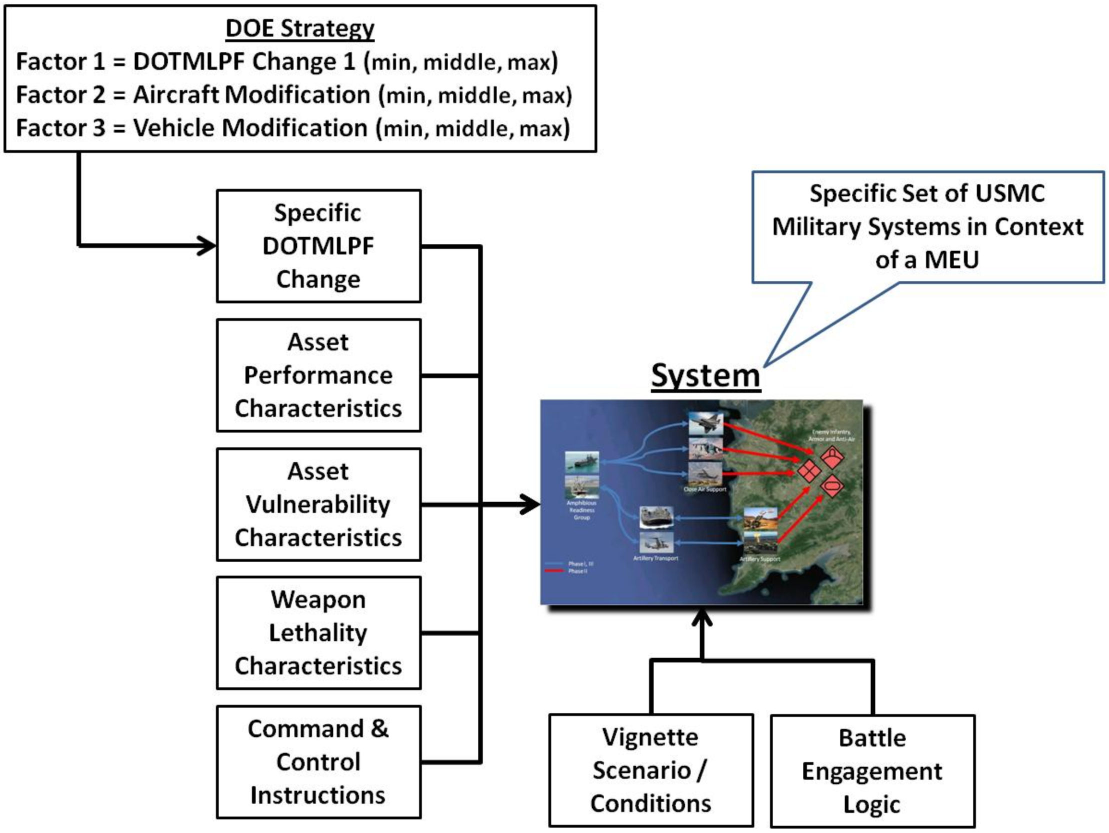

Figure 4. Input / Output Model — System Inputs

As shown in Figure 5, output information from the system was defined to be fuel usage, battle length, and loss or casualty data. Also shown in this figure was how the output information was used to perform a design of experiments (DOE) analysis from which efficient frontier plots were produced.

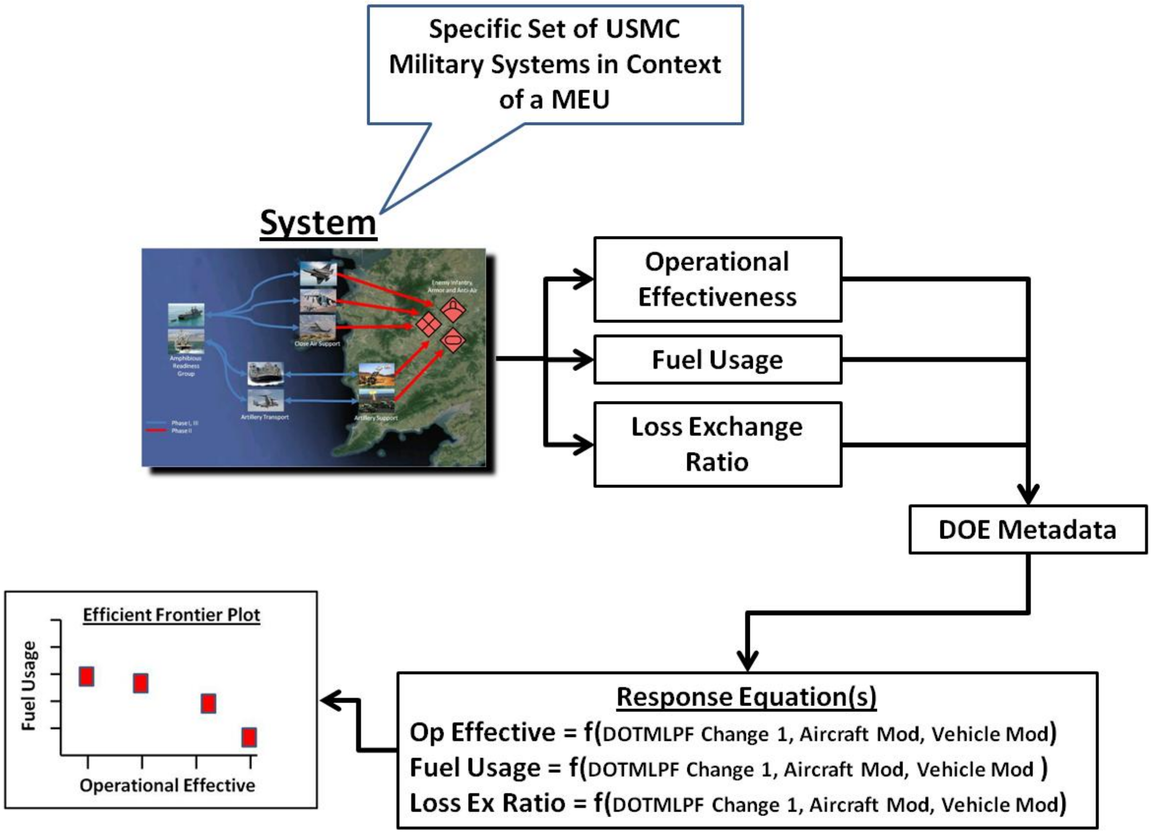

Figure 5. Input / Output Model — System Outputs

E. VIGNETTES

Phase one begins with all attack platforms positioned on the amphibious readiness group ships. The ships include a combination of Dock Landing Ship (LSD), Landing Platform/Dock (LPD), and Landing Helicopter Dock (LHD). Phase one continues with a decision to attack with aviation and/or ground platforms. If the decision is to attack with aviation pure, then the assets available include the F-35B, the AV-8B, the AH-1Z or the UH-1Y. If the decision is to engage the target set via ground platforms, then they are transported to their firing positions by a Landing Craft Air Cushion (LCAC), a CH-53K King Stallian, or an MV-22 Osprey. Phase two begins in either case by engaging the target sets. The target sets include a low threat, medium threat, and high threat. The target sets for each threat level utilizes the Opposing Force Operations publication, constructed by Headquarters, Department of the Army. The low threat for these vignettes includes; a 60mm mortar section, a platoon-sized element of insurgents, and insurgents in trucks.

The medium threat includes; a 120mm mortar squad, an infantry company with SA-18 MANPADS, and a BRDM-2 platoon. The high threat template includes; a 120mm mortar platoon, a reinforced infantry company with SA-18 MANPADS, a BMP-2 platoon (CAS model only), a T-72 platoon, and a 2S6 platoon. The phase concludes upon the successful removal of the specified target set or when the friendly forces are no longer capable of engaging targets. Phase three involves the return of aviation attack assets and the transport of ground platforms back to the ship. The vignettes developed were based on the team's experience and used to describe the flow of events. The flow of events identified what functions need to be performed in each phase of the engagement. The vignettes are described in more detail in the following sections.

F. BATTLE ENGAGEMENT SCENARIOS

The battle engagement scenarios were developed in order to build our model and run simulations. Still utilizing the three phases described in the operational concept, the battle engagement scenarios show an air attack pure concept and ground attack pure concept. Analysis of each engagement scenario, including environmental independent variables, decision independent variables, and weapon to target priority, assisted in determining the optimal energy efficient method while not detracting from operational effectiveness.

1. Aviation Attack Pure Engagement Vignette

The first set of battle engagement scenarios includes an aviation attack pure engagement. Pure is defined in this case as the sole use of aviation assets for the purpose of attacking during the engagement. Shown in Figure 6, the aviation attack pure consists of three phases and begins with the commander identifying the threat and considering decision variables such as force structure and ammunition load out. The first two scenarios within these vignettes utilized fixed wing assets only. One scenario simulated the use of AV-8Bs as the close-air-support (CAS) platform while another scenario simulated the F-35B. The third and fourth scenarios within this vignette mixed rotary wing (AH-1Z/UH-1Y) with either the AV-8B or the F-35B. The CAS platform launched from the ship to a planned pre-positioning location in preparation for engagement. The

CAS platforms engaged the target sets of low, medium, and high threat levels with either maneuver forces observers or unmanned aerial systems. If the weaponeering selected achieved the desired effects, then the CAS platforms returned to the ship. If the desired effects were not achieved, then the scenario continued in a cyclic process until the effects were achieved.

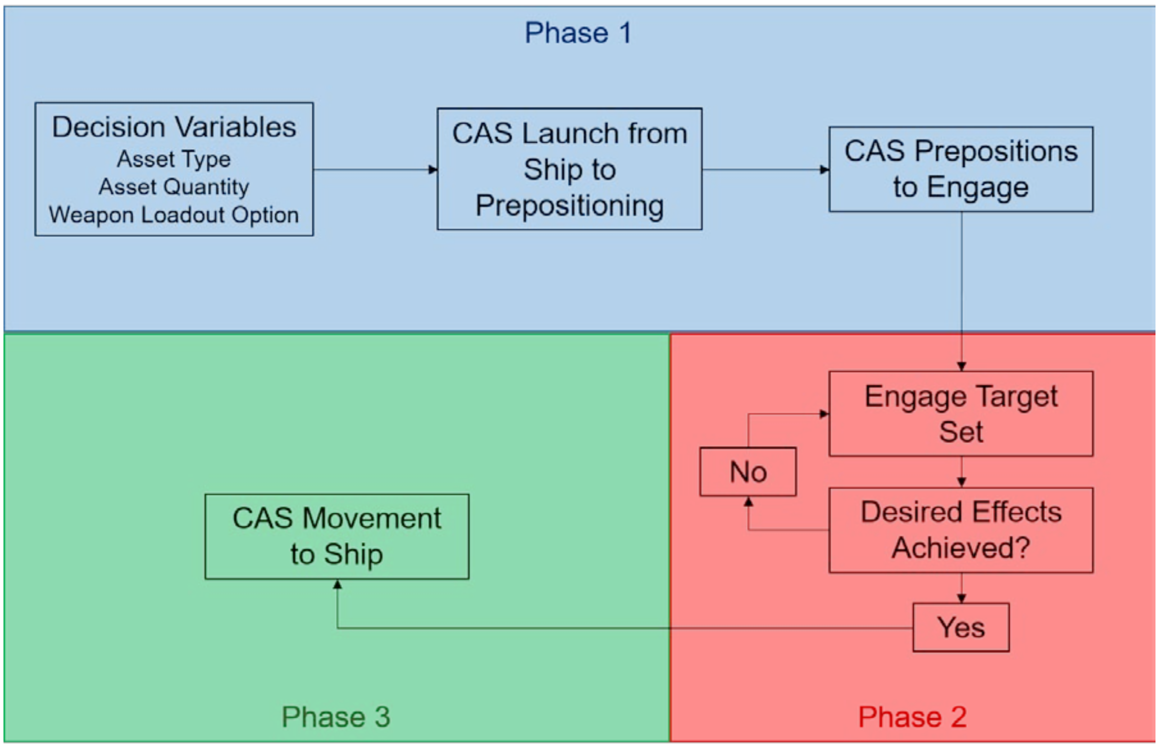

Figure 6. Aviation Attack Pure Battle Engagement Scenario

2. Ground Attack Pure Engagement Vignette

The second battle engagement scenario included a ground attack pure engagement. Pure is defined in this case as the sole use of ground assets for the purpose of attacking during the engagement. Shown in Figure 7, the ground attack pure also consisted of three phases and began with the commander identifying the threat and considering decision variables such as force structure and ammunition load out. This vignette included two scenarios: one simulating only M777A2 howitzers and the second simulating both M777A2 howitzers and the EFSS. The ground attack platforms were

transported either by sea transport or by air transport and then debarked and moved to the position area for artillery in preparation for engagement. In a similar fashion to the aviation attack pure scenario, the ground platforms engaged the target sets of low, medium, and high threat. If the effects were not achieved, then the ground platforms re-attacked by expending a different munitions type or firing more rounds. Upon successful engagement of the target set, the ground platforms moved from the objective to the shore and embarked. The scenario concluded with all platforms returned to the ships.

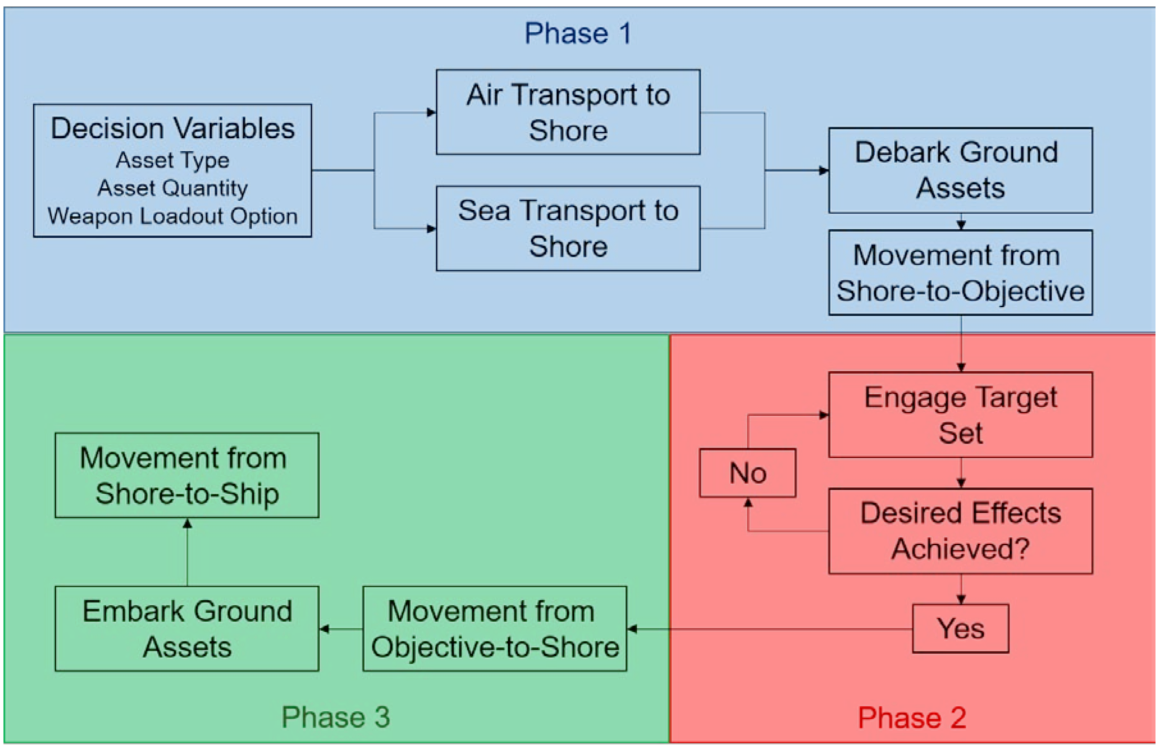

Figure 7. Ground Attack Pure Battle Engagement Scenario

G. SUMMARY

Using the first step of the tailored-SE Vee, the team defined the problem and developed an initial system concept. As described above, the effective need of the Marine Corps was the identification of changes to tactics and techniques, in the context of an MEU operation, that a) improve fuel usage while maintaining operational effectiveness or b) maintain existing fuel usage but provide increased operational effectiveness. Conduct

of the need/gap analysis resulted in the identification of the capability required, which was a specific change or set of changes to current tactics and techniques associated with an MEU operation that a) provide improved fuel usage while maintaining operational effectiveness or b) maintain existing fuel usage but provide increased operational effectiveness. Based on the capability needed, the initial system modeled was identified as a specific set of Marine Corps military systems operating in the context of an MEU. The context of the MEU was determined based on research analysis conducted using Expeditionary Warrior 2014 (*Expeditionary Warrior* 2014b*)* and included ship-to-shore and return movements, CAS maneuvers, and GCS maneuvers.

An Input / Output model was constructed and input items such as aircraft and vehicle performance, weapon system lethality, and vignette and battle engagement logic were defined. Output items from the system, such as fuel usage, battle length, and loss exchange ratio, were also defined. Vignettes were developed to define the battle engagement scenarios of a CAS and GCS mission.

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III. SYSTEM ARCHITECTURE

This chapter describes step 2 and 3 of the SE process: develop system functions, flow of information, and identify components that meet the defined functions of the MEU system. The second step of the tailored-SE Vee focused on developing a hierarchical model of the functions performed by the system and the tracing of information flow both inside and external to the system. The activities completed in this second step were: a) develop hierarchical model of system functions, b) develop system functional flow block diagram, c) develop a hierarchy of system functions, d) develop Measures of Effectiveness (MOE) and Measures of Performance (MOP), e) develop a set of originating requirements (including qualification requirements) for the system, f) trace originating requirements and MOEs/MOPs to appropriate system functions, and g) identify a set of qualification requirements to be used to verify the performance of the system. According to Buede, the physical architecture provides the resources for each identified function in a system (Buede 2000). The results obtained from step 2 were documented as the system functional architecture and used as input to step 3 of the tailored-SE Vee to identify the physical components assigned to those functions.

A. FUNCTIONAL ARCHITECTURE

1. System Functions

The functional architecture was developed by conducting an analysis to identify the functions, tasks, or activities necessary for the MEU to achieve mission success. The result of this analysis formed an integrated description of the functional architecture and was the basis for development of specific requirements. For this study, a functional analysis was performed to identify the functions necessary to achieve the capabilities identified by the effective need. The functional analysis conducted resulted in the development of a functional overview, a functional hierarchy, and functional flow block diagrams.

a. Functional Overview

Based on the information obtained during the literature search and stakeholder analysis, the project team developed a high level functional overview. The primary purpose of this high level functional overview, shown in Figure 8, was to determine the overall system and boundaries. By providing an initial visual overview, the project team was assured that development of the functional architecture was created with the right focus. The figure shows various data points being inputs into an operational scenario: DOTMLPF changes, asset performance characteristics, asset vulnerability characteristics, weapon lethality characteristics, and command and control (C2) instructions. These inputs are used within a defined scenario with programmed battle engagement logic of both the blue and red forces. The system within the scenario is an MEU with a specific mix of assets. Given the defined system within the scenario the outputs obtained from various simulations were operational effectiveness, fuel usage, etc.

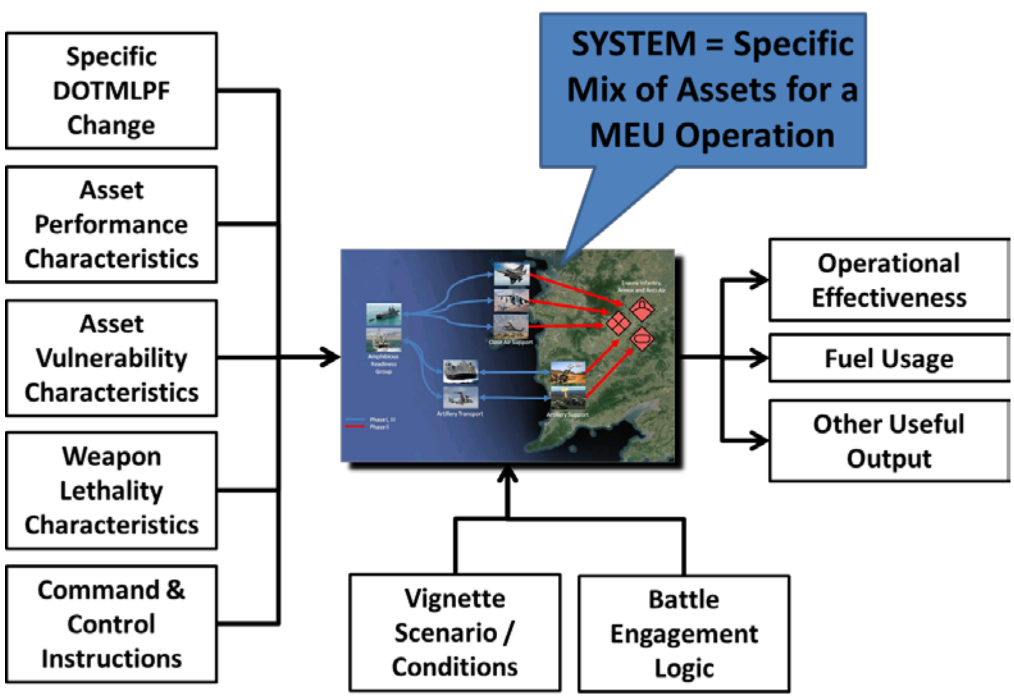

Figure 8. Functional Overview

b. Functional Hierarchy

The MEU was decomposed into the necessary system functions to achieve mission success. The method used to identify and present these functions was the hierarchy of functions, which is shown in Figure 9. Using this functional overview, further decomposition was conducted to focus on the function of interest from the literature research: Conduct Amphibious Raid. Figure 10 identifies the functional decomposition of the MEU function Conduct Amphibious Raid.

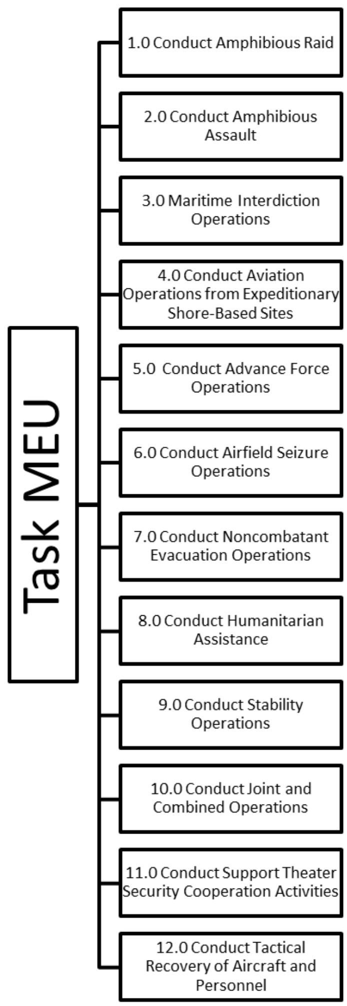

Figure 9. MEU System Level Functions (adapted from *NAVMC 3500.99* 2012)

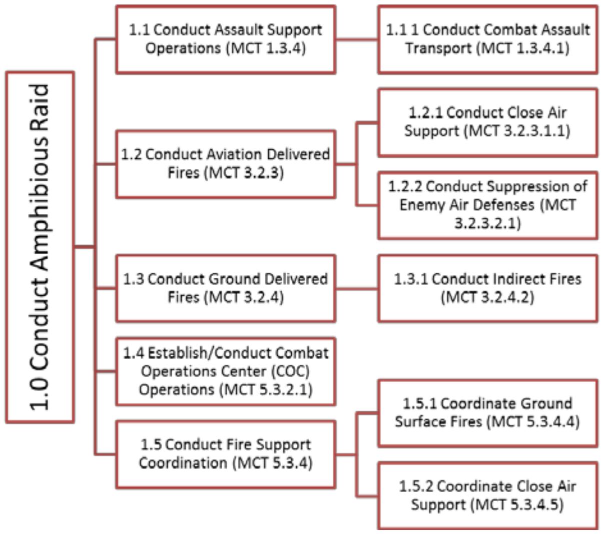

Figure 10. Conduct Amphibious Raid Functional Decomposition (adapted from *MCO 3500.26* 2015)

The sub-functions of Conduct Amphibious Raid were defined and shown in Table 2 using the Marine Corps Task List, July 2015 to narrow in on specific sub-functions of interest to model. Three sub-functions captured the stakeholder area of interest: function 1.1 covered logistics support during an assault mission, function 1.2.1 covered close air support, and function 1.3.1 covered ground combat support. These three sub-functions of an MEU were modeled in order to adjust DOTMLPF areas to determine effects on operational effectiveness and fuel usage.

Table 2. Functional Description (*Marine Corps Task List* 2015)

Function	Description
1.1 Conduct Assault Support	"Assault support uses aircraft to provide tactical mobility and logistic support to the MAGTF for the movement of high priority personnel and cargo within the immediate area of operations (or the evacuation of personnel and cargo). It also uses Marine aerial refueler transport squadrons (VMGRs) to provide in-flight refueling. Assault support gives the MEF Commander the mobility to focus and sustain his combat power at decisive places and times. It allows the MEF

Function	Description
	Commander to take full advantage of fleeting battlespace opportunities. There are three levels of assault support: tactical, strategic, and operational.”
1.1.1 Conduct Combat Assault Transport	“Aviation combat assault transport operations provide mobility to the MAGTF. It is used to deploy forces (air-landed or air-delivered) efficiently in offensive maneuver warfare, bypass obstacles, or quickly redeploy forces. Combat assault support allows the MAGTF Commander to build up his forces rapidly at a specific time and location, and allows him to apply and sustain combat power and strike the enemy where he is unprepared. This function comprises those actions required for the airlift of personnel, supplies and equipment into or within the battle area by helicopter, tiltrotor or fixed-wing aircraft. “
1.2 Conduct Aviation Delivered Fires	“The MAGTF Commander, based on recommendations by the ACE Commander, determines the allocation of aviation effort within the MAGTF. The air section assists the current fires section and is directly responsible for all matters pertaining to the use of aviation fire assets in battle. It maintains close contact with the Marine Tactical Air Command Center (TACC), monitors the Air Tasking Order (ATO), and focuses on reactive targeting in the MAGTF deep battle per targeting principles. Electronic attack is considered a form of fires.”
1.2.1 Conduct Close Air Support	“Close Air Support (CAS) operations are performed by fixed-wing and rotary-wing aircraft against hostile targets that are in close proximity to friendly forces. CAS requires detailed integration of each air mission with the fire and movement of friendly forces. It includes preplanned and immediate close air support (CAS) missions, positive identification of

Function	Description
	friendly forces and positive control of aircraft, and enhances ground force operations by delivering a wide range of weapons and massed firepower at decisive points.”
1.2.2 Conduct Suppression of Enemy Air Defenses	“Suppression of Enemy Air Defenses (SEAD) missions coordinate, integrate, and synchronize attacks, which neutralize, destroy, or temporarily degrades surface or subsurface-based enemy air defenses by destructive and/or disruptive means.”
1.3 Conduct Ground Delivered Fires	“To conduct ground delivered fires that directly support land, maritime, amphibious, and special operations forces to engage enemy forces, combat formations, and facilities in pursuit of tactical and operational objectives. The ground combat element (GCE) plans, integrates, and coordinates all fire support for its own artillery and mortar fires within its area of operations, and integrates fires with maneuver in close operations. Surface-to-surface joint fire support includes organic Army and Marine Corps artillery, rocket, missile, and naval surface fire support (NSFS) systems. NSFS includes the enhanced capabilities of Navy fire support ships, to include the addition of missiles.”
1.3.1 Conduct Indirect Fires	“To apply indirect fire ground-based weapon systems to delay, disrupt, destroy, suppress, or neutralize enemy, equipment (including aircraft on the ground), materiel, personnel, fortifications, and facilities.”
1.4 Establish / Conduct Combat Operations Center Operations	“To establish and conduct operations in a combat operations center (COC) which support the headquarters of all units of battalion size or larger. Watch officers and cells from the various staff sections, plan, monitor, coordinate, control, and support the day-to-day activities of the unit. The COC is the command’s ‘nerve center’ where information is fused to provide

Function	Description
	situational awareness for the Commander and his staff. To provide controls and procedures for tactical movement of forces in a way that permits a Commander to move his force quickly, securely, and efficiently. To take into account the size of units and related time and space factors. To pass on multiple routes at a designated speed, organized in serial march units; establish jamming teams and liaison parties; and move tactical command post before main body to synchronize and coordinate movement, etc. Control is established to ensure the Commander flexibility to deploy his force as necessary for tactical purposes."
1.5 Conduct Fire Support Coordination	"To coordinate the employment of lethal fires against hostile targets which are in close proximity to friendly forces to assist land and amphibious forces to maneuver and control territory, populations, and key waters. Fire support can include the use of close air support (CAS) (by both fixed- and rotary-wing aircraft), naval surface fire support (NSFS), land-based fire support, Special Operations Forces, as well as, some elements of electronic warfare (EW)."
1.5.1 Coordinate Ground Surface Fires	"To coordinate artillery and mortar support with maneuver of forces ashore, into a cohesive action maximizing their effect in accomplishing the mission and minimizing adverse effects on friendly/ neutral forces and non-combatants."
1.5.2 Coordinate Close Air Support	"To coordinate Close Air Support (CAS) with maneuver of forces ashore into a cohesive action maximizing their effect in accomplishing the mission and minimizing adverse effects on friendly/ neutral forces and non-combatants."

c. Functional Flow Block Diagram

According to Buede, FFBDs provide a “hierarchical decomposition of the system’s functions with a control structure that dictates the order in which the functions can be executed at each level of decomposition” (Buede 2009). The focus of the FFBD is to illustrate which functions occur and when relative to each other. No emphasis is placed on identification of inputs to or outputs from each of these functions. The top level FFBD for the conduct of an MEU Conducting an Amphibious Raid is shown in Figure 11. This FFBD identified that 1.1 Conduct Assault Support Operations must occur prior to 1.2.1 Conduct Close Air Support or 1.3.1 Conduct Indirect Fires. The figure also identifies that in a realistic engagement functions 1.2, 1.2.1, 1.2.2, 1.3, and 1.3.1 would be occurring simultaneously. For the purposes of focusing on the effects of DOTMLPF adjustments on CAS and GCS 1.2.1 and 1.3.1 were modeled separately instead of engaging a mission simultaneously.

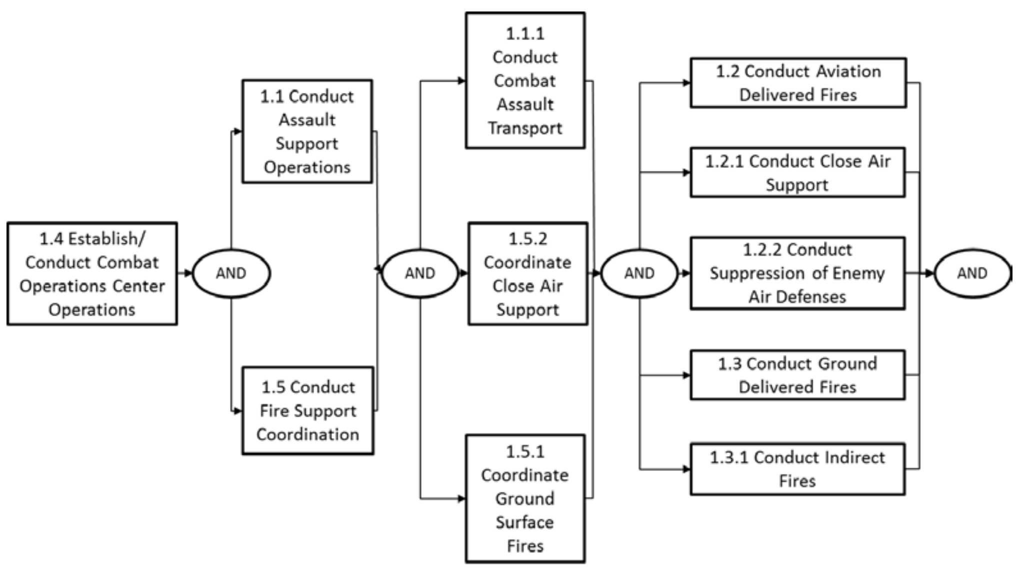

Figure 11. MEU Functional Flow Block Diagram

2. Hierarchy of System Objectives

Buede states that the “objectives hierarchy of a system is the hierarchy of objectives important to system’s stakeholders in a value sense” (Buede 2000). They would be willing to pay more for these objectives in order to obtain increased system

performance or obtain a net decrease in system costs. Fundamental objectives are generally top level and describe an overall objective from which more specific objectives are derived. For this system, the following fundamental objectives were identified from the *USMC Expeditionary Energy Strategy and Implementation Plan* (2011c).

1. maximize operational effectiveness
2. minimize overall fuel usage
3. minimize blue force casualties
4. maximize red force neutralization

These objectives were determined by using the goals of the DOD and E2O during a battle engagement scenario. Each objective is linked to a measure of performance, which traces back to a measure of effectiveness and function as described in the next section.

3. Measures of Effectiveness and Measures of Performance

A measure of effectiveness (MOE) "describes how well a system carries out a task or set of tasks within a specific context" (Buede 2009). According to Buede, MOE's can be defined based on the major outputs of a system (Buede 2009). A measure of performance (MOP) "describes a specific system property or attribute of the system" (Buede 2009). An MOP forms the basis of an originating or high level requirement and is measured within the system. Table 3 identifies the MOEs and MOPs for each function being modeled for this project.

Table 3. MOE and MOP Functional Traceability

Function	MOE	MOP
1.1 Conduct Assault Support	MOE 1: Percentage of mission window covered	MOP 1: Fuel consumption MOP 2: Length of mission window (time)
1.2.1 Conduct Close Air Support	MOE 2: Percentage of blue forces lost MOE 3: Percentage of targets neutralized	MOP 3: Length of mission (time) MOP 4: Number of targets neutralized MOP 5: Number of blue force assets destroyed
1.3.1 Conduct Indirect Fires	MOE 4: Percentage of blue forces lost MOE 5: Percentage of targets neutralized	MOP 6: Length of mission (time) MOP 7: Number of targets neutralized MOP 8: Number of blue force assets destroyed

Each objective identified in the previous section links with the traceability in Table 3. Objective 1, maximize operational effectiveness, is traceable to MOP 2 – MOP 8, which capture how successful the mission was. Objective 2, minimize overall fuel usage, is traceable to MOP 1, which captures the total fuel consumption. Objective 3, minimize blue force casualties, is traceable to MOP 5 and MOP 8, which capture the number of CAS and GCS assets destroyed. Objective 4, maximize red force neutralization, is traceable to MOP 4 and MOP 7, which capture the number of red force targets neutralized.

4. Originating Requirements

According to Buede, originating requirements are developed based on the following four categories: "a) input/output requirements, b) system wide and technology requirements, c) tradeoff requirements, and d) qualification requirements" (Buede 2000). Input/output requirements are generally based on the information contained in the external systems diagram. System wide and technology requirements are typically related to technology, suitability, cost, and schedule. For this system and because of project constraints, no system wide and technology requirements were identified. Trade off requirements generally take the form of value curves and are based on fundamental objectives identified in the objectives hierarchy. Qualification requirements determine how the qualification data will be: a) obtained, b) used to verify the system, c) used to validate the system, and d) used to determine the system is satisfactory to stakeholders. For this system, the following originating requirements were identified. The top level requirement for the system is to achieve desired level of effect while performing and mission.

1. The system shall include the modeling of the F-35B and Harrier systems;
2. The system shall include the modeling of the Howitzer and the 7 ton, medium tactical vehicle replacement (MTVR);
3. The system shall include the modeling of the EFSS to include the 120mm mortar, two Internally Transportable – Light Strike Vehicles (IT-LSV), and ammunition trailer;
4. The system shall include the modeling of the LCAC and the MV22 aircraft;

5. The system shall model either a CAS vignette (aviation attack vignette) or ship-to-shore movement to support an indirect fire engagement (ground attack vignette);
6. For the ground attack vignette, the system shall model blue forces that utilize the Howitzer, EFSS and 7 ton MTVR truck. For the aviation attack vignette, the system shall model blue forces that utilize the F-35B and Harrier aircraft;
7. Red forces shall have decision making capability based on blue force actions;
8. Dependent variables (output from the system) shall include fuel usage and operational effectiveness;
9. Independent variables (input to the system) shall be based on DOTMLPF aspects of an MEU and at a minimum address tactics, techniques, and ground vehicle modifications, and aircraft modifications;
10. The ExtendSim model shall simulate the major actions of the operational scenario as discrete events. Performance of various components of the simulation shall be modeled using probability distributions in order to produce a non-deterministic solution;

B. PHYSICAL ARCHITECTURE

Having completed the functional architecture, the next step in the SE process was to develop the generic physical architecture of the system or in this case the methodology. The generic physical architecture was developed by initially identifying and assigning generic components to accomplish the functions identified in the functional architecture. For the system being developed, the primary components of the generic physical architecture consisted of the initial MEU configuration, CAS components, and GCS components.

1. MEU Component identification

Using stakeholders' feedback and the experience of the team members the blue force components or assets were identified to complete each function as well as the red force assets to be neutralized. Marine Corps Order 3120.9C (dated August 4, 2009) was used to define the doctrinal composition of an MEU. Ground elements such as infantry platoons and mortar teams are assumed to operate according to doctrine and will not have numerical representation in the simulation. The blue force assets are identified in Table 4.

Table 4. Blue Force Assets to Perform Marine Corps Tasks

Function	Available Assets
1.1 Conduct Assault Support	MV-22B Osprey, CH-53K King Stallion, KC-130J Marine Super Hercules, AH-1Z Super Cobra, UH-1Y Huey, Landing Helicopter Dock (LHD), Landing Platform/dock (LPD), Landing Ship Dock (LSD), Landing Craft Air Cushion (LCAC)
1.2.1 Conduct Close Air Support	AV-8B Harrier, F-35B Joint Strike Fighter
1.3.1 Conduct Indirect Fires	M777A2 howitzer, Expeditionary Fire Support System (EFSS), Medium Tactical Vehicle Replacement (MTVR), Internally Transportable – Light Strike Vehicle (IT-LSV)

The assets in function 1.1 fulfill logistic support. MV-22B and CH-53K aircraft as well as LCAC's were used to transport troops, supplies, ground assets, and conduct casualty evacuation (CASEVAC) and retrograde functions. MTVRs were utilized for transport on land for all artillery assets of the MEU. IT-LSV escorts the MTVR when artillery assets were transported on land. As described earlier in previous sections, the amphibious readiness group includes the LHD, LPD, and LSD. These ships provided the home base for all of the assets, acting as a connector to the Navy and Marine Corps. KC-130J aircraft provided some supply transport but mainly fulfilled the refuel requirements for CAS missions. The fuel consumption of the LHD, LPD, and LSD were not modeled in order to focus on CAS and GCS assets and operations. The fuel consumption of the LCAC was taken into account during the GCS model in order to compare the asset transit medium of sea or air.

Members of this team include artillery officers and a fighter pilot who bring their working knowledge to the project. Their knowledge has helped identify the CAS and GCS components as described in the following sections.

2. CAS Component Identification

Each blue force CAS asset carried a weapon load out as characterized in Table 5. Option 1 identifies the current doctrinal weapon load out of modeled assets and option 2 identifies the potential future capability of weapon loading based upon lessons learned

from the ongoing conflicts and acquisition plans. The F-35B was authorized to carry one GBU-12 500-pound laser guided bomb and one GBU-32 1,000-pound GPS guided bomb without sacrificing low observable characteristics that result from equipping the aircraft with munitions outside of its weapons bays. Both the AV-8B and F-35B would sacrifice one bomb in order to be equipped with a gun, which requires being attached to the aircraft in a similar fashion to a bomb.

The GBU-54 dual mode laser/GPS guided 500-pound bomb is becoming more desired by ground units due to the increased versatility of employment environments (Engdahl 2015). It has yet to be adopted as doctrine. The United States Air Force is currently testing the GBU-53B low collateral, dual mode laser/GPS guided 250-pound bomb. It is expected to have better precision and, due to its lightweight, be carried in higher quantities than current munitions. This translates to more targets struck by a single aircraft (Engdahl 2015). It is expected to IOC around 2018 with F-35B incorporation coming in 2022 (Osborn 2015).

Rotary wing assets are equipped with the M197 20 millimeter (mm) cannon, Advanced Precision Kill Weapons System (APKWS) 70mm laser guided rockets, M229 2.75 inch unguided rocket and the AGM-114K2A enhanced Hellfire laser guided rocket. Specific quantities carried by each air asset are depicted below. The numbers represent the doctrinal amounts carried for each piece of weaponry, therefore, under Option1 of the AH-1Z in the M197 cell, 1,000 indicated the number of 20mm rounds carried by the AH-1Z. In the model, the firing rate was captured with a normal distribution of 100 rounds per shot with a standard deviation of 50 rounds. Distributions of weapons are described in Table 5.

Table 5. CAS Weapon Loadout Options

	Option 1 Assets (Doctrine)				Option 2 Assets (Future Capability)			
Weapon	AV-8B	F-35B	AH-1Z	UH-1Y	AV-8B	F-35B	AH-1Z	UH-1Y
GBU-12	1	1						
GBU-32		1						
GBU-38	1							
GBU-54					2			
M197			1000	4000			1000	4000
M229			14				14	
APKWS				7				7
AGM-114K2A			4				4	
GBU-53/B						4		

3. GCS Component Identification

The GCS model simulated the M777A2 and EFSS as ground force artillery assets. When artillery assets were transported by an air medium the GCS model simulated the MV-22B, CH-53K, KC-130J, AH-1Z, and UH-1Y. When artillery assets were transported by a sea medium the GCS model simulated the LCAC, MTVR, and IT-LSV.

The GCS model incorporated two indirect fire weapon systems, the 120mm EFSS and the 155mm M777A2 howitzer. For each of the weapon systems a conventional and precision munition loadout were defined. Additionally, the weapon systems were transported from the MEU ships to the shore via a surface or air based connector. The surface based connector used for both weapon systems was the LCAC. The aerial based connector used for the EFSS is the MV-22B and for the M777A2 was the CH-53K.

The different munitions modeled in conjunction with the EFSS were the M1101 high explosive round for the conventional loadout and the M1109 Precision Extended Range Munition (PERM) for the precision loadout. Of note, the M1109 is currently still under development and is scheduled to be fielded in FY18 (Marine Corps Systems Command 2014).

The Howitzer has the ability to employ a multitude of projectiles, however, this model focused on precision munitions. The first precision munition included the M795 high explosive projectile with a precision guidance kit that was fuzed with it. The second precision munition was the M982 Excalibur projectile, which was a more precise and accurate projectile.

C. SUMMARY

A functional analysis was performed of the MEU system, decomposing the function of interest: Conduct Amphibious Raid. Three sub-functions were chosen to model due to stakeholder interest. A hierarchy of objectives was developed and several resulting MOEs and MOPs defined, specifically those related to operational effectiveness and fuel usage. A set of top level originating requirements for the system were defined, several of which addressed specific stakeholder input such as the use of the F35B aircraft and the requirement for red force decision making. The physical architecture of the system or in this case the methodology was developed, identifying the MEU operation and specific assets and components involved in the modeled CAS and GCS scenarios.

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IV. DESIGN

The fourth step of the SE process builds from the physical architecture identifying components of the MEU. In this step the characteristics of the physical components are defined and modeled within an operational scenario, which includes fuel consumption rates weapon characteristics, and probability of the desired effects. Initial discussion on the model independent variables is also included in this step.

A. COMPONENT CHARACTERISTICS

1. Blue Force Characteristics

The characteristics of the blue force assets were inputted into the CAS and GCS models. Each asset is characterized by its fuel consumption, weapon load out, and probability of effects. For the AV-8B asset, fuel data was compiled from the Naval Air Training and Operating Procedures Standardization (NATOPS) flight manual (Chief of Naval Operations and Naval Air Systems Command, 2011). For the MV-22B asset, fuel data was compiled from the NATOPS flight manual (Chief of Naval Operations and Naval Air Systems Command, 2014a). For the UH-1Y asset, fuel data was compiled from the NATOPS flight manual (Chief of Naval Operations and Naval Air Systems Command, 2014b). For the AH-1Z asset, fuel data was compiled from the NATOPS flight manual (Chief of Naval Operations and Naval Air Systems Command, 2014). For the CH-53E asset, fuel data was compiled from the NATOPS flight manual (Chief of Naval Operations and Naval Air Systems Command, 2015). Ground vehicle operating characteristics and fuel data were estimated for cross country operation based on observed highway conditions (Program Executive Officer Land Systems 2013). LCAC operating characteristics and fuel data were extracted from the LCAC employment reference guide (Naval Doctrine Command 1997).

Members of this team include artillery officers and a fighter pilot who bring their working knowledge to the project. Their knowledge has helped identify the CAS and GCS component characteristics in the following sections.

a. Fuel Consumption Characteristics

Table 6 identifies the fuel rates for blue air assets with a payload. Aviation assets are broken down into: start, taxi and takeoff (STTO), climb to altitude, cruise to target area, tactical employment, refuel and landing rates. Fuel burn for a helicopter during climb assumed a 10 minute loiter time at a maximum endurance airspeed or power setting. Cruise fuel rates assumed a maximum range airspeed or power setting. Due to the effect of temperature on fuel burn rates, a cold and hot matrix was used capture the effect to operational effectiveness. It was assumed the KC-130J, CH-53K, and MV-22B burn 20% less fuel when not carrying a payload.

Table 6. Aviation Fuel Consumption with Payload

	Average Temperature Rates					
Asset	Takeoff	Climb	Cruise	Tactical	Refuel Rate	Landing
KC-130J	700 lbs	1700 lbs	5,600 lb/hr	7,200 lb/hr	1,900 lb/min	300 lbs
AV-8B	500 lbs	400 lbs	4,800 lb/hr	10,800 lb/hr	2,000 lb/min	500 lbs
F-35B	1100 lbs	2000 lbs	5,700 lb/hr	9,000 lb/hr	2,000 lb/min	1,100 lbs
AH-1Z	50 lbs	150 lbs	800 lb/hr	1100 lb/hr	500 lb/min	50 lbs
UH-1Y	50 lbs	150 lbs	800 lb/hr	1100 lb/hr	500 lb/min	50 lbs
CH-53K	400 lbs	200 lbs	2600 lb/hr	2,900 lb/hr	2,000 lb/min	400 lbs
MV-22B	200 lbs	500 lbs	3100 lb/hr	4,300 lb/hr	2,000 lb/min	200 lbs
	Cold Temperature Rates					
	Takeoff	Climb	Cruise	Tactical	Refuel Rate	Landing
KC-130J	600 lbs	1700 lbs	5,600 lb/hr	7,200 lb/hr	1,900 lb/min	300 lbs
AV-8B	400 lbs	400lbs	4,800 lb/hr	10,800 lb/hr	2,000 lb/min	500 lbs
F-35B	900 lbs	2000 lbs	5,700 lb/hr	9,000 lb/hr	2,000 lb/min	1,100 lbs

(continued on next page)

Table 6 (continued from previous page)

AH-1Z	50 lbs	150 lbs	600 lb/hr	1100 lb/hr	500 lb/min	50 lbs
UH-1Y	50 lbs	150 lbs	600 lb/hr	1100 lb/hr	500 lb/min	50 lbs
CH-53K	350 lbs	200 lbs	2300 lb/hr	2,900 lb/hr	2,000 lb/min	400 lbs
MV-22B	150 lbs	500 lbs	2900 lb/hr	4,300 lb/hr	2,000 lb/min	200 lbs
	Hot Temperature					
	Takeoff	Climb	Cruise	Tactical	Refuel Rate	Landing
KC-130J	900 lbs	1700 lbs	5,600 lb/hr	7,200 lb/hr	1,900 lb/min	300 lbs
AV-8B	700 lbs	400lbs	4,800 lb/hr	10,800 lb/hr	2,000 lb/min	500 lbs
F-35B	1200 lbs	2000 lbs	5,700 lb/hr	9,000 lb/hr	2,000 lb/min	1,100 lbs
AH-1Z	100 lbs	150 lbs	900 lb/hr	1200 lb/hr	500 lb/min	50 lbs
UH-1Y	100 lbs	150 lbs	900 lb/hr	1200 lb/hr	500 lb/min	50 lbs
CH-53K	450 lbs	200 lbs	2700 lb/hr	3,100 lb/hr	2,000 lb/min	400 lbs
MV-22B	300 lbs	500 lbs	3200 lb/hr	4,500 lb/hr	2,000 lb/min	200 lbs

The air asset fuel characteristics were needed for capturing total mission time in both the CAS and GCS models. The fuel tank capacity determined how long the air assets could operate until refueling was needed and these values are shown in Table 7.

Table 7. Air Asset Fuel Characteristics

Asset	Fuel Tank Capacity (lbs)
KC-130J	85,000
AH-1Z	2,750
UH-1Y	2,600
CH-53K	20,600
MV-22B	6,750
AV-8B	11,750
F-35B	13,500

In addition to the air asset fuel characteristics, the ground and sea asset fuel consumption characteristics were needed for the GCS model. The ground asset characteristics determined the total scenario fuel consumption and the time spent refueling during the scenario and are shown in Table 8.

Table 8. Ground Asset Fuel Characteristics

Asset	Idle (gph)	Moving with Payload (mpg)	Refuel Rate (gal/min)	Fuel Tank Capacity (gal)	Refuel Rate (gal/min)
MTVR	1.9	3.9	10	80	10
ITV	0	11.1	10	25	10

The sea asset fuel characteristics were needed when the GCS elements were transited by the sea medium. These characteristics determined the total scenario fuel consumption by sea and are shown in Table 9. The fuel tank capacity and refueling rate are not shown since it is assumed that the LCAC gets refueled by the host ship, which does not impact total mission time.

Table 9. Sea Asset Fuel Characteristics

Asset	Low Sea State (lbs)	Avg Sea State (lbs)	High Sea State (lbs)
LCAC	700	800	1000

b. Asset Speed Characteristics

The speed characteristics of the blue force assets were used to determine total scenario time for both the CAS and GCS models. Data was taken from operator observed data as well as the platform specific NATOPS manual. The air asset speed characteristics are shown in Table 10.

Table 10. Air Asset Speed Characteristics

	Cruise Speed (kts)	Tactical Speed (kts)	Cruise Speed (mph)	Tactical Speed (mph)	Post-mission turnaround time
KC-130J	200	240	227	273	2.5 hrs
AH-1Z	100	140	114	159	1.5 hrs
UH-1Y	100	140	114	159	1.5 hrs
CH-53K	130	170	131	148	2.5 hrs
MV-22B	160	260	182	295	3.0 hrs
AV-8B	300	450	341	511	2.5 hrs
F-35B	300	350	345	403	2.5 hrs

The ground asset speed characteristics assumed a constant cross country terrain during the scenario and are shown in Table 11.

Table 11. Ground Asset Speed Characteristics

Asset	Speed (mph)
MTVR	15
ITV	30

The only sea asset that influenced total scenario time was the LCAC. The speed characteristics of the LCAC varied depending on sea state and are shown in Table 12.

Table 12. Sea Asset Speed Characteristics

Asset	Low Sea State (kts)	Avg Sea State (kts)	High Sea State (kts)
LCAC	38	32	4

c. ***Probability of Desired Effect***

Probability of desired effect (Pd) is used to determine the success or failure of an attack. Pd is not a probability of hit or miss but a more comprehensive metric as to whether the weapon achieves the desired effect against a specified target set. This includes variables such as errors in target location, errors in guidance and delivery and

how effective the damage mechanism of the munition is against the defenses of the target. Five standard desired effects to be achieved against our target sets were selected from Appendix G of the Joint Munitions Effectiveness Manual Air to Surface Weaponeering Guide (JTCG/ME 2009) and are listed in Table 13.

Table 13. Desired Effect Definitions

Desired Effect	Definition
30-sec Defense	Incapacitation that will render personnel unable to perform in a defending role within 30 seconds of wounding.
M-20 kill	Damage sufficient to render a vehicle (or ship) incapable of executing controlled movement within 20 minutes and damage is not repairable by the crew on the battlefield.
5-min Assault	Incapacitation that will render personnel unable to perform in an assaulting role within 5 minutes of wounding.
F-kill	Damage to the target such that its ability to use its armament is lost (i.e., can no longer accurately fire its weapons) and damage is not repairable by the crew on the battlefield.
MSN-kill	Measure of the degree of target damage that prevents the target from completing its designated mission; however, it is not attrited from inventory. Specifically, for radars and satellite communications: neutralization of those functions that are necessary for the radar to search and detect targets for some period of time.

Table 14 identifies the probability of desired effect of a blue force weapon engaging a red force target. These are unclassified average probabilities derived from weapons experts in both aviation and ground fires communities, graduates of the Weapons and Tactics Instructors course in Yuma, AZ. Proportional effectiveness between weapons systems was maintained, however, for the purposes of classification, the true values were excluded.

In a real world CAS scenario, the determination of a weapon achieving a desired effect is assessed by someone within sight of the target. This can come from a forward observer (FO), Joint Terminal Attack Controller (JTAC), or Forward Air Controller-Airborne (FAC(A)). In this simulation it is assumed an FO is attached to the EFSS or M777A2 and at least one UH-1Y or AH-1Z crew are qualified as FAC(A) to make the determination of desired effect. Additionally, per doctrine, there would be one JTAC per company of infantry to make the assessment.

The blue force weapon systems are listed in the far left column and the red force threats are listed in the first row. For each red force threat a certain level of neutralization is desired and is listed in the desired effects row. Each desired effect is defined in Table 13. It has been assumed that if the simulation registers a successful attack, the notional blue ground forces conduct their doctrinal tactics to eliminate the threat.

Table 14. CAS Weapon to Target Probability of Desired Effect

		Insurgents (Qty 32)	Insurgents in Truck	60mm Mortar Section	120mm Mortar Section	SA-18 w/ Infantry Company	BRDM-2 Platoon	BMP-2 Platoon	T-72 Tank Platoon	2S6 Battery
	Desired Effects	30-sec defense	M-20 kill	5-min assault	5-min assault	5-min assault	M-20 kill	M-20 kill	F-kill	MSN -kill
Weapon System	**M982**	0.8	0.8	0.8	0.8	0.8	0.8	0.65	0.6	0.8
	M795	0.6	0.6	0.6	0.6	0.6	0.42	0.5	0.4	0.6
	M1109	0.7	0.7	0.7	0.7	0.7	0.42	0.55	0.45	0.7
	M1101	0.45	0.45	0.45	0.45	0.45	0.25	0.35	0.25	0.45
	GBU-12	0.42	0.8	0.42	0.42	0.42	0.8	0.8	0.6	0.8
	GBU-32 VT	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.25	0.6
	GBU-38 VT	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.25	0.6
	GBU-53/B	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.07	0.42
	GBU-54	0.6	0.8	0.6	0.6	0.6	0.8	0.8	0.6	0.8
	M197	0.42	0.6	0.6	0.6	0.6	0.6	0.6	0.42	0.6
	M229	0.42	0.25	0.6	0.6	0.6	0.25	0.25	0.07	0.6
	APKWS	0.6	0.25	0.6	0.6	0.6	0.25	0.25	0.07	0.6
	AGM-114K2A	0.25	0.8	0.6	0.6	0.6	0.8	0.8	0.8	0.42

The GCS model varied the type of munitions of the M777A2 and EFSS as well as the quantity of tubes for each. There are two loadout options for each artillery asset, one that uses conventional munitions, and one that uses precision munitions. The probability of desired effect on various red force threats for each loadout option are shown. The number of tubes are varied for each munition option and their probability of desired effect shown respectively. The probability of desired effect with these variables are shown in Table 15.

Table 15. Probability of Desired Effect for GCS Weapons Loadout Options

Red Force Threat			Insurgents (Qty 32)	Insurgents in Truck	60mm Mortar Section	120mm Mortar Section	SA-18 w/ Inf Company	BRDM-2 Platoon	T-72 Tank Platoon	2S6 Battery
Desired Effect			30-sec defense	M-20 kill	5-min assault	5-min assault	5-min assault	M-20 Kill	F-kill	MSN-kill
Number of volleys			2	3	2	4	2	4	7	5
M777A2	Conventional Munition # of Tubes	1	0.10	0.10	0.10	0.10	0.10	0.08	0.07	0.10
		2	0.20	0.20	0.20	0.20	0.20	0.17	0.13	0.20
		3	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.30
		4	0.40	0.40	0.40	0.40	0.40	0.33	0.27	0.40
		5	0.50	0.50	0.50	0.50	0.50	0.42	0.33	0.50
		6	0.60	0.60	0.60	0.60	0.60	0.50	0.40	0.60
	Precision Munition # of Tubes	1	0.13	0.13	0.13	0.13	0.13	0.11	0.08	0.13
		2	0.27	0.27	0.27	0.27	0.27	0.22	0.17	0.27
		3	0.40	0.40	0.40	0.40	0.40	0.33	0.25	0.40
		4	0.53	0.53	0.53	0.53	0.53	0.43	0.33	0.53
		5	0.67	0.67	0.67	0.67	0.67	0.54	0.42	0.67
		6	0.80	0.80	0.80	0.80	0.80	0.65	0.50	0.80
EFSS	Conventional Munition	1	0.06	0.06	0.06	0.06	0.06	0.04	0.03	0.06
		2	0.11	0.11	0.11	0.11	0.11	0.09	0.06	0.11
		3	0.17	0.17	0.17	0.17	0.17	0.13	0.09	0.17
		4	0.23	0.23	0.23	0.23	0.23	0.18	0.13	0.23

(continued on next page)

Table 15 (continued from previous page)

		5	0.28	0.28	0.28	0.28	0.28	0.22	0.16	0.28
		6	0.34	0.34	0.34	0.34	0.34	0.26	0.19	0.34
		7	0.39	0.39	0.39	0.39	0.39	0.31	0.22	0.39
		8	0.45	0.45	0.45	0.45	0.45	0.35	0.25	0.45
	Precision Munition # of Tubes	1	0.09	0.09	0.09	0.09	0.09	0.07	0.06	0.09
		2	0.18	0.18	0.18	0.18	0.18	0.14	0.11	0.18
		3	0.26	0.26	0.26	0.26	0.26	0.21	0.17	0.26
		4	0.35	0.35	0.35	0.35	0.35	0.28	0.23	0.35
		5	0.44	0.44	0.44	0.44	0.44	0.34	0.28	0.44
		6	0.53	0.53	0.53	0.53	0.53	0.41	0.34	0.53
		7	0.61	0.61	0.61	0.61	0.61	0.48	0.39	0.61
		8	0.70	0.70	0.70	0.70	0.70	0.55	0.45	0.70

2. Red Force Characteristics

The red force assets were structured as low, medium and high threat scenarios. Construction was based on Former Soviet Union (FSU) threat compositions that are prevalent throughout USMC areas of operations. Table 16 identifies the red force structure at the various threat levels for both the CAS and GCS models. Quantities were captured from the website Federation of American Scientists at http://www.fas.org. To capture tactical realities, if certain threats were present, the blue force launch or employment options shifted. An example being the 2S6; if this threat was present, all rotary wing aircraft were unavailable due to the high probability of being hit. All rotary wing operations were halted until the 2S6 was destroyed by either ground assets or fixed wing. It can be seen from the table that the BMP-2 platoon was only present in the CAS high threat level. This threat should have been present in both the CAS and GCS models, but was an oversight that was found too late in the analysis. With more time this threat would have been incorporated into the GCS model and the simulations re-run for analysis.

Table 16. Red Force Threat Level Structure

Threat Level	Assets	Quantity
Low	60 mm Mortar Section	2
	Insurgents (Qty 32)	3
	Insurgents in Truck	3
Medium	120 mm Mortar Squad	1
	Infantry Company with SA-18	6
	BRDM-2 Platoon	4
High	120mm Mortar Platoon	4
	Strong Infantry Company with SA-18	6
	BMP-2 Platoon (CAS model only)	3
	T-72 Platoon	3
	2S6 Platoon	2

For each level of red force threat different weapons were used. The threat range of each weapon used by the red forces and the probability of neutralization are shown in Table 17. Probability of neutralization was used instead of probability of damage because the ExtendSim software limited the simulation to outputting binary results of the asset being neutralized or operational. There was no probability of neutralization for fixed wing and rotary wing assets for certain enemy threats because the blue force assets were always outside the threat range of the identified red force weapon. Aviation assets were also only subject to a threat if weather or lack of other assets required it. As an example, there was no fixed wing asset on station in the medium threat, aviation only scenario. This means the rotary wing assets had to assume higher risk in order eliminate the SA-18. Of note, due to classification level, the F-35B probability of neutralization was not captured and results in higher blue force losses than can be expected in real-world missions. Both the AV-8B and F-35B utilized the below probability of neutralization for the simulation.

Table 17. Red Force Weapon Threat Range and Probability of Neutralization

		Threat Ranges (m)		Probability of Neutralization			
Threat Level	Enemy Threat	Horizontal	Vertical	Fixed Wing	Rotary Wing	M777A2	EFSS
Low	60mm Mortar Section	2573	0	-	-	0.1	0.1
	Insurgents (Qty 32)	800	800	-	-	0.05	0.05
	Insurgents in Truck	800	800	-	-	0.05	0.05
Medium	120mm Mortar Squad	8135	0	-	-	0.2	0.2
	Infantry Company w/ SA-18	7000	7700	0.5	0.8	0.1	0.1
	BRDM-2 Platoon	2000	0	-	-	0.1	0.1
High	120mm Mortar Platoon	8135	0	-	-	0.3	0.3
	Infantry Company (+) w/ SA-18	10000	7700	0.5	0.8	0.2	0.2
	BMP-2 Platoon	4000	0	-	-	-	-
	T-72 Platoon	5000	0	-	-	0.4	0.4
	2S6 Platoon	2600/10000	6100/9900	0.75	0.9	-	-

B. CAS INDEPENDENT VARIABLES

Through the functional analysis the capabilities of the MEU were identified, specifically for conducting assault support operations. To address the problem, potential doctrine and materiel changes were identified and translated into decision independent variables for the discrete event simulation of the assault support operational scenario. Additionally, environmental independent variables were identified in order to determine

the fuel usage and operational mission effects. A total of nine independent variables were identified for the CAS discrete event simulation. Further discussion of the independent variables is in the remaining sections of the report.

1. Decision Independent Variables

Five decision independent variables were determined for the CAS simulation that can be characterized as either materiel solution changes or doctrine changes. One of the decision independent variable was weapons load out options, which is shown in Table 5. The four additional decision variables were: aircraft asset, ship-to-shore distance, total assets available and assets used per launch. Ship-to-shore distances were defined as the transit distance required by aircraft from their host ship to the target area. Aircraft asset captured changes to the materiel solution, and the remaining variables captured changes to doctrine. Detailed numerical breakdowns of each variable are identified in the remaining chapters.

Each decision independent variable was linked back to a MEU function. Weapons load out was traced back to function 1.2.1 Conduct Close Air Support. The weapons load out directly supported conducting a successful close air support mission. The selection of aircraft asset, ship-to-shore distance, total assets available and assets used per launch directly supported function 1.2.1 Conduct Close Air Support and function 1.1 Conduct Assault Support. These four decision variables were elements that impacted the success of conducting close air support, and were also elements that impacted the logistics support in function 1.1.

2. Environmental Independent Variables

Weather had significant impact on tactical decisions as well as performance characteristics of military assets. For this reason, weather effects on operational effectiveness and fuel were also examined. Four environmental independent variables were identified to account for fuel usage and operational effectiveness: temperature, sea state, cloud coverage, and red force threat level. MEU operations stipulate certain sea state requirements for aviation and LCAC operations. If wave heights exceeded a certain value, those assets could not be utilized. Similarly, cloud cover affected the ability of

certain assets to have the desired effects or even employment of munitions. An example being if there were low clouds in the target area, laser guided bombs from fixed wings assets could not be employed. Temperature changes affected aviation asset fuel burn rates, a known variable, but the overall relationship between operational effectiveness and the other variables was examined. Numerical breakdowns of each variable are detailed in the following sections.

C. GCS INDEPENDENT VARIABLES

Through the functional analysis the capabilities of the MEU while conducting GCS were identified. Similar to the CAS simulation, potential doctrine and materiel changes were identified and translated into decision independent variables for the discrete event simulation. Additionally, environmental independent variables were identified in order to determine the fuel usage and operational mission effects. A total of ten independent variables were identified for the GCS discrete event simulation. Further discussion of the independent variables is in the remaining sections of the report.

1. Decision Independent Variables

Six decision independent variables were determined for the GCS simulation that can be characterized as either materiel solution changes or doctrine changes. One of the decision independent variable is weapons load out options, which is shown in Table 6. The five additional decision variables are: weapon type, transit medium, ship-to-shore distance, total weapons quantity, and quantity of assets transited per launch medium. Materiel solutions are captured by varying the artillery weapon type used in the scenario as well as the weapon loadout. Doctrine changes are captured by varying between sea and air as the GCS element transit medium, the ship-to-shore distance, which is defined as the sea transit distance from the host ship to the shore area, the total quantity of weapons, and the quantity of assets transited per launch. Detailed numerical breakdowns of each variable are identified in the remaining chapters.

Each GCS decision independent variable was linked back to a MEU function. Weapons load out, weapon type, and total weapons quantity was traced back to function 1.3.1 Conduct Indirect Fires. These three functions directly supported conducting a

successful ground combat support mission. The selection of ship-to-shore distance and quantity of assets transited per launch medium directly supported function 1.3.1 Conduct Indirect Fires and function 1.1 Conduct Assault Support. These two decision variable were elements that impacted the success of conducting ground combat support operations and were also elements that impacted logistics support in function 1.1. The selection of transit medium directly supported the logistics function 1.1 Conduct Assault Support.

2. Environmental Independent Variables

Weather had significant impact on tactical decisions as well as performance characteristics of military assets. For this reason, weather effects on operational effectiveness and fuel were also examined. Four environmental independent variables were identified to account for fuel usage and operational effectiveness outcomes: temperature, sea state, red force threat level, and the ship-to-firing distance. Cloud cover did not change artillery effectiveness or fuel consumption, so it was not a factor in the GCS model. Temperature changes affected aviation asset fuel burn rates, but did not affect sea or ground asset fuel rates. Ship-to-firing distance is defined as the air transit distance from the host ship to the firing location. Numerical breakdowns of each variable are detailed in the following sections.

D. SUMMARY

The characteristics of the CAS and GCS assets were identified by building from the physical architecture of the MEU. The characteristics of the blue and red forces used for the discrete event simulation described in the next chapter were defined in this section. This chapter introduces the independent variables for the operational scenarios, which are discussed in further detail in the next chapters.

V. VERIFY COMPONENT DESIGN

The fifth step of the SE process verifies that the physical components meet the performance requirements identified in step three. The output from this step was the verified generic physical architecture and a summary assessment of how well each component met its required performance. In order to verify the system, a discrete event model was created to simulate the scenario. This section details the modeling methodology of the scenario creation.

A. MODELING METHODOLOGY

Discrete event simulation software, ExtendSim, was used for the modeling of the battlespace. The vignettes and engagement scenarios developed in the first step of the SE process were used as the basis for the simulation models. Each vignette and engagement scenario was a discrete model.

1. Modeling Constraints and Assumptions

There were several constraints in modeling the scenario:

- Ground asset engagements were modeled at the company size level.
- Air asset engagements were limited to single sortie missions.
- The MEU had to maintain operational effectiveness.
- There was a limited amount of deck space on the MEU.

There were several assumptions that were made when creating the model:

- Air superiority had been achieved. Enemy air assets had been eliminated and were no longer a risk.
- Enemy surface to air missile installations had been neutralized for all but high threat environments.
- Radar early warning system capabilities had been degraded.
- Air defense assets were limited to anti-air guns and shoulder fired missiles.
- Risks to off-shore assets were negligible.
- The only ground assets available in the company were MTVR, IT-LSV, M777A2 and EFSS.
- Ground assets disembarked at the staged firing position when transported by air.

- Artillery were placed at the staging point and no ground vehicles were involved in the mission when ground artillery were transported by air.
- The MTVR remained idle for the duration of the engagement once they arrive at the artillery staging area.
- Mission terrain was consistently cross country.
- Risk to the air transport assets was negligible. During the GCS mission the air assets were not engaged by red forces and did not engage red forces.
- Blue forces continued to pursue the highest red threat until it was neutralized, then the blue forces pursued the next highest threat.
- Aircraft fuel consumption was 20% lower when not carrying payload.
- The UH-1Y had no additional external fuel tank.
- The same mix of escort aircraft was used regardless if the CH-53 or MV-22 was transporting artillery.
- Fuel usage of the mission-area-transit state for transport assets was negligible.
- The number of transport assets required to transport ground assets remained the same for both the transit-to-mission-area state and transit-to-ship states regardless of number of ground assets still operational.

2. Simulation Flow

This section details the different stages of the simulation, the inputs and outputs of the simulation, and how casualties were modeled. All the simulation models began with a transit stage followed by a mission execution stage, and a final transit stage. The first transit stage modeled the transit from the ship to the mission area and the second transit stage modeled the transit from the mission area to the ship. The top level simulation flow for the CAS and GCS models is shown in Figure 12. It identifies three phases of events starting with STTO and transit, moving into conducting the mission, and ending with returning to base. Within each phase assets followed their characteristic simulation flow. The individual simulation flow of each asset is shown in Appendix B.

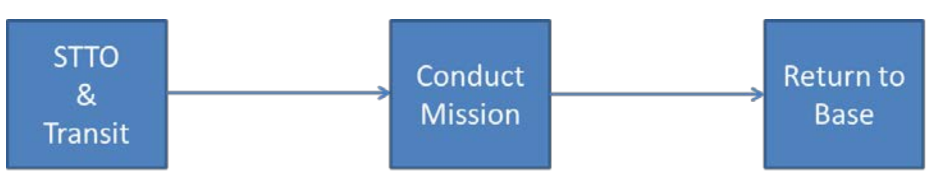

Figure 12. CAS Top Level Simulation Flow

A simulation flow for an asset conducting a CAS operation is shown in Figure 13. A simulation flow for an asset conducting a GCS operation is shown in Figure 14. The CAS and GCS models had similar structure and simulation flow but differed in some aspects. In the CAS simulation, each air asset selected the appropriate munition based on the target and if the munition was unavailable, then the asset used the next appropriate munition. In the GCS simulation, the ground assets were grouped as one unit with one type of munition, which resulted in only checking munitions available. Cloud coverage affected the probability of achieving the desired effect against a target in the CAS model. It also affected the probability of destroying a blue asset. Cloud coverage was not used in the GCS model. Finally, in the CAS model, air assets transitioned to the phase of returning to base when the air asset expended all of their munitions, or all the targets had been neutralized. Ground assets in the GCS model transitioned to the phase of returning to base when all units expended all of their munitions, had been destroyed, or when all targets had been destroyed.

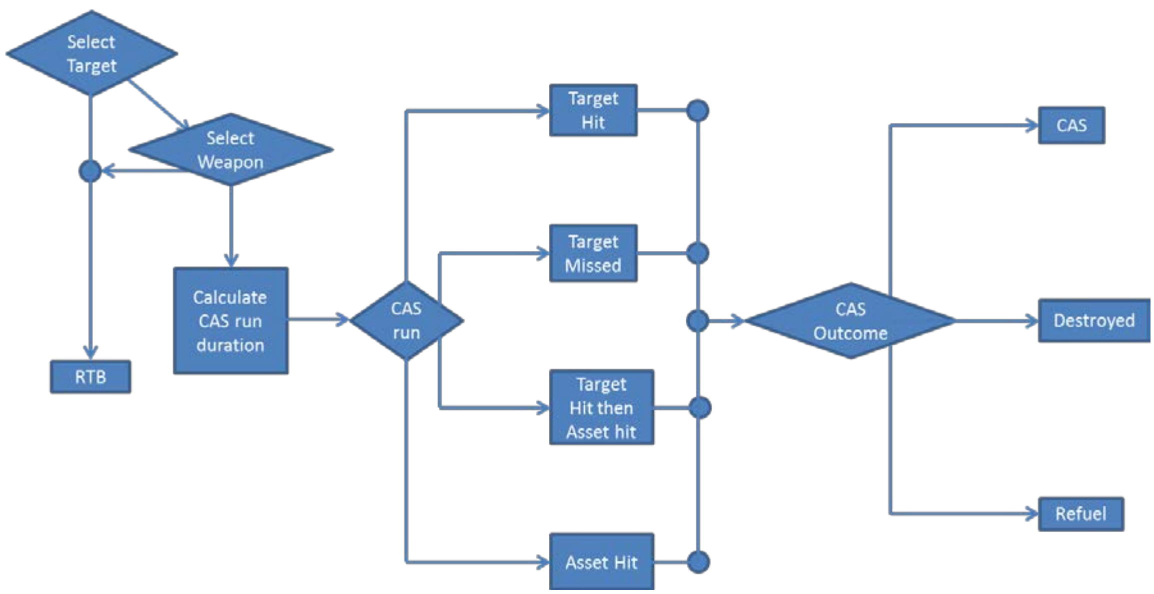

Figure 13. CAS Simulation Flow for an Asset

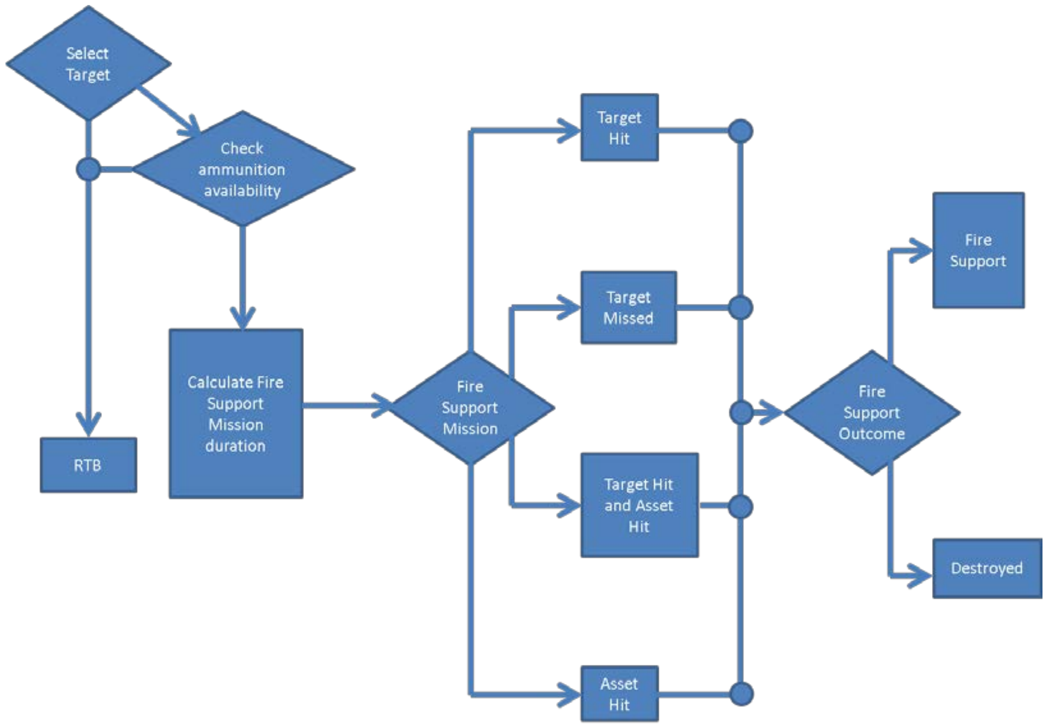

Figure 14. GCS Simulation Flow for an Asset

a. *Start, Taxi, Take-off and Transit Stage*

There are two types of transit stages in each simulation model, transit-to-mission-area and transit-to-ship. In the case of the air asset model, the transit-to-mission-area stage is composed of a takeoff-and-assemble state followed by a transit state as shown in Figure 15 by the blue blocks. During takeoff-and-assemble stage, each air asset will takeoff sequentially and wait in the assembly area until all air assets have assembled before transitioning to the transit state where all air assets will head to the mission area as one unit. The transit-to-ship stage is composed of a return-transit state followed by a landing state. During the return-transit state, the air assets will head back to the ship as a single unit or as a group depending on the outcome of the mission. Once the air assets reached the ship, the air assets will land sequentially. During the mission fuel rate and time will be recorded from each stage, and will require all of the simulation settings to complete the mission as highlighted in red in Figure 15.

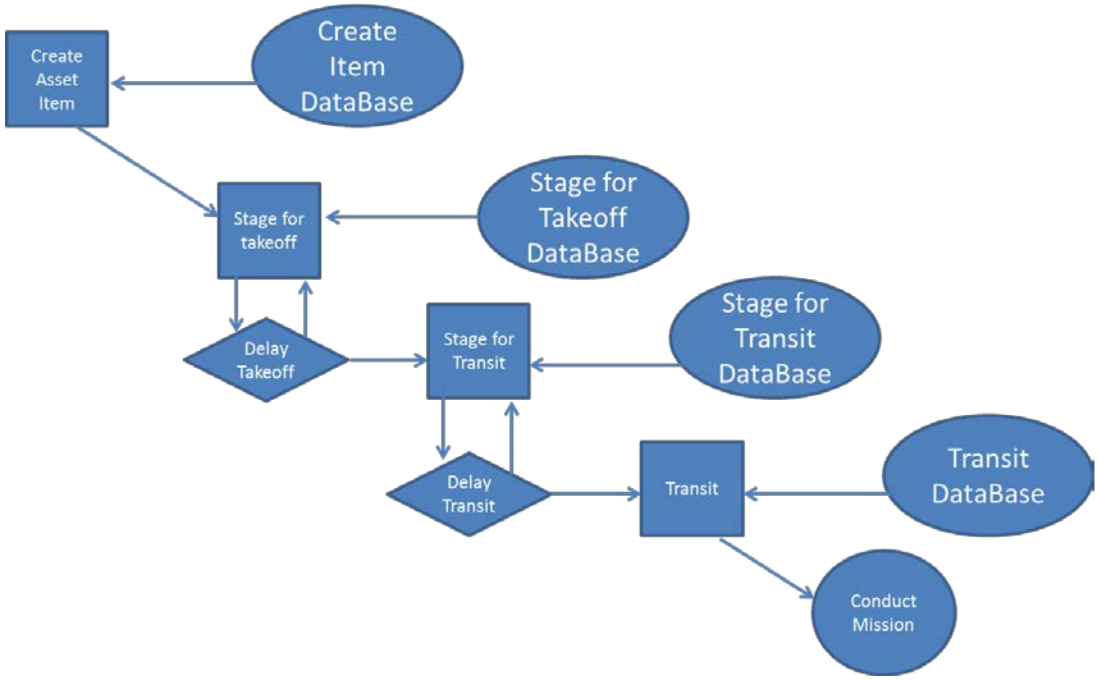

Figure 15. Transit to Mission Area Stage

In the case of the ground asset model, the transit-to-mission-area stage depended on the medium that was used for transport. In the case of a sea lift transport, the transit-to-mission-area stage was composed of a ship-to-shore-connector state followed by a mission-area-transit state. The transit-to-ship stage was composed of a transit-to-rally state followed by a ship-transit state. During the ship-to-shore-connector state, ground assets were transported to shore via a ship-to-shore connector such as LCACs and then they disembarked. The ship-to-shore connector transited back to the ship and transported any remaining ground assets to shore. The ship-to-shore-connector state concluded once all the ground assets had been transported to shore and the mission-area-transit state begun. During this state, the ship-to-shore connectors transited back to the ship and waited, while the ground assets continued to the mission area. During the transit-to-rally state of the transit-to-ship stage, both the ship-to-shore connectors and the ground assets proceeded to the pickup point for embarkation. Once the ground assets had embarked to the ship-to-shore connectors, the transit-to-ship stage transitioned to the ship-transit state. As with the ship-to-shore-connector state, the ship-to-shore connectors transited back to shore and transported any remaining ground assets to the ship.

b. *Conduct Mission Stage*

There are two types of conduct mission stage: an air asset conduct mission stage and a ground asset mission execution stage. The air asset mission execution stage consists of a waiting state and an attack state. During the loiter state, the air assets will wait until it is called on to attack. During the attack state, the air assets will attack the target with the specified munitions and return to the loiter state. Air assets may transition to the transit-to-ship stage if all munitions have been expended or the air assets reach a minimum fuel state required to return to the ship. If the desired effect has been obtained then all remaining air assets will transition to the transit-to-ship stage. The simulation flow of conducting the mission is shown in Figure 16.

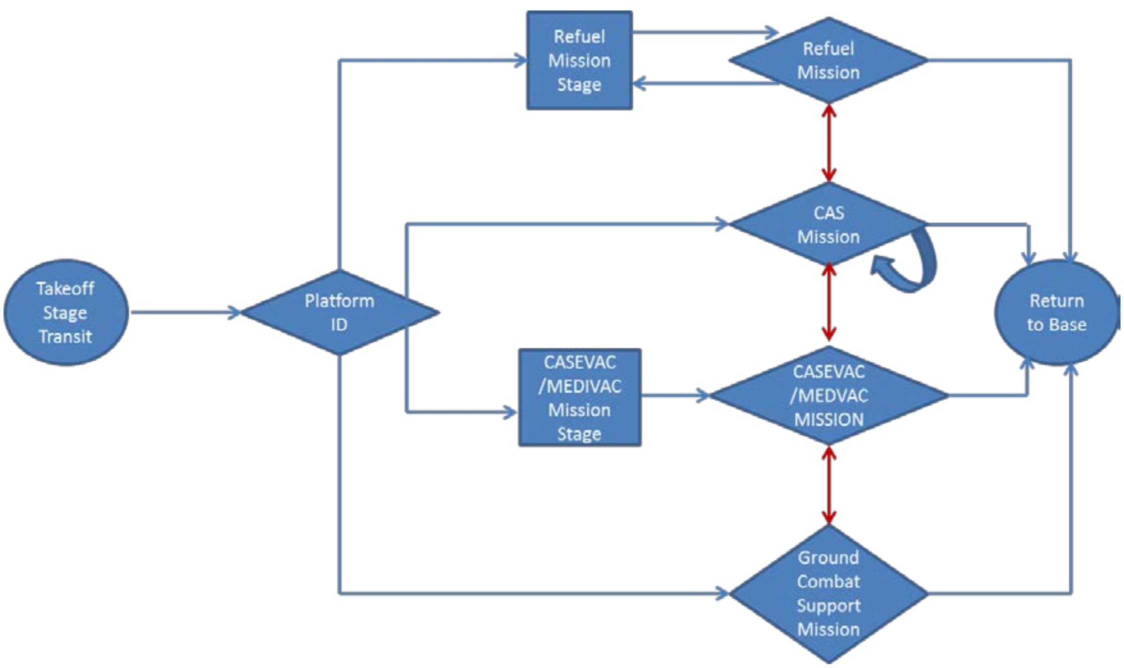

Figure 16. Conduct Mission Simulation Flow

The ground assets were grouped with their respective platform and modeled as one unit with the number of artillery pieces as an attribute. The ground asset conduct mission state consisted of a ready state, and an attack state. During the ready state, the ground assets waited until they were called upon to attack. During the attack state, the

ground assets engaged the enemy with artillery. The higher the number of artillery pieces in a unit, the higher the probability of achieving the desired effect on the target. The exit criterion for this stage was the completion of the mission objectives or the destruction of all the artillery pieces in the unit.

3. CAS Model Inputs

The inputs and outputs for the model were stored in Excel spreadsheets. The data that was used as inputs were:

- independent variables captured as variation in asset quantities or type, variation in fuel consumption, variation in probability of desired effect, or variation in probability of neutralization
- fuel consumption rates of assets
- red force threat level structure
- asset to target priorities
- weapon to target priorities
- probabilities of desired effect
- probabilities of neutralization
- asset launching sequence
- asset speed

The model inputs that were independent variables are shown in Table 18 and Table 19. There were nine independent variables, or factors: environmental variables (temperature, sea state and cloud cover, red force threat level), type of blue force assets, quantity of assets, launch number, ship-to-shore distance, loadout option. The inputs consisted of environmental independent variables and decision independent variables as noted in the previous chapter. The environmental conditions independent variables are uncontrollable during a battle engagement scenario, but their effect on a scenario is of interest. The decision independent variables are variables the USMC can adjust through doctrine or asset changes to achieve a desired outcome. Additional information that was inputted to the model was a look up table or normal distribution of values for: priority of which weapon used to neutralize a target, probability of neutralizing red force targets with a given blue force weapon, and probability of blue force asset neutralization. The model inputs were based on stakeholder input on assets of interest and team member experience on doctrine.

Weather conditions such as temperature, sea state, and cloud cover were considered as inputs to the model and are shown in Table 18. The environmental conditions were shown as ranges, and were incorporated into the model by adjusting asset fuel consumption, weapon effectiveness, or probability of neutralization accordingly. For example, specifying cold temperatures in a simulation run resulted in certain fuel consumption rates of air assets being used. Similarly, specifying overcast cloud cover resulted in certain probability of desired effect and probability of neutralization values to be used. Values for temperature were chosen based on significant fuel use changes at those temperatures. Sea state values were chosen based on the World Meteorological Organization code and the restrictions on operations defined by MCO 3120.9C. Cloud cover values were chosen based on significant weapon and aircraft system performance changes due to clouds.

Table 18. CAS Environmental Conditions Independent Variables

Environmental Independent Variable	Options	Metric	Range
Weather	Cold	Temp (˚F)	< 40
	Average		> 40 , < 80
	Hot		> 80
Sea State	Calm	Wave Height (feet)	< 1
	Choppy		> 1 , < 8
	Rough		> 8
Cloud Cover	Clear / High	Cloud Base Above Ground (feet)	> 25k
	Broken / Mid		< 25k , > 5k
	Overcast / Low		< 5k
Red Force Threat Level	Low	Type of Assets	See Table 16
	Medium		
	High		

There were five decision independent variables that were varied to represent doctrine and materiel adjustments in a CAS scenario. The five variables and their ranges are shown in Table 19. Weapon loadout options are defined in Table 5.

Table 19. CAS Decision Independent Variables

Decision Independent Variable	Options (Physical Traceability)	Metric	Range	Functional Traceability
Type of Aircraft	F-35B	--	--	1.2.1 Conduct Close Air Support and 1.1 Conduct Assault Support
	AV-8B		--	
Weapon Loadout	Option 1	Weapon Type	See Table 5	1.2.1 Conduct Close Air Support
	Option 2			
Number of Total Assets Per Type	Low	Percent of Doctrine	< 80%	1.2.1 Conduct Close Air Support and 1.1 Conduct Assault Support
	Average		> 80% , < 115%	
	High		> 115%	
Number of Assets Per Launch	Low	Percent of Doctrine	<50%	1.2.1 Conduct Close Air Support and 1.1 Conduct Assault Support
	Average		>50%, <150%	
	High		>150%	
Distance to Shore	Near	Nautical Miles	60	1.2.1 Conduct Close Air Support and 1.1 Conduct Assault Support
	Average		100	
	Far		300	

Aircraft type and weapon loadout were discussed in previous sections. By varying the total number of assets, assets per launch and distance to shore, changes to existing doctrine and tactics were evaluated. The total number of assets available to a commander was adjusted based on a percentage of the doctrine amount currently used. This assumes all assets are operationally available and there exists a capacity to hold the increase in assets on the naval ships. 80% and 115% of doctrine were chosen to show realistic

potential changes into the size of individual squadrons and to ensure statistical changes could be captured. Assets used per launch were varied from 50% to 150% of doctrine numbers to capture the effect of tactical adjustments to the nearest whole number. 150% represents a surge of forces, while 50% represents decreased asset availability due to maintenance or commander discretion. A variation that existed was if doctrine use was one aircraft. Decreasing to 50% is not possible, so the doctrine amount was maintained. This occurred only for the KC-130J and AH-1Z, UH-1Y sections. Distance to shore is taken from MCO 3120.9C, which is based on USMC and U.S. Navy input, and represents a change to not only USMC doctrine, but the U.S. Navy as well.

The remaining input values for the CAS model that have not been documented in previous chapters are described in this section. The launch sequence depicted in Table 20 is directly derived from MCO 3120.9C and is a result of ship deck size, size of the asset launching, and side-effects of the asset launching, such as high heat and wind generation from the exhaust during an AV-8B vertical launch.

Table 20. Launch Sequence (from MCO 3120.9C)

Launch Sequence	First	Second	Third	Fourth	Fifth	Sixth	Seventh	Notes	
1	CH-53	KC-130	MV-22B	AV-8B	AV-8B	AV-8B	AV-8B	AV-8B launch every 45min	
2	CH-53	KC-130	MV-22B	F-35B	F-35B	F-35B	F-35B	F-35B launch every 45min	
3	CH-53	AH-1/UH1	KC-130	MV-22B	AH-1/UH-1	AV-8B	AH-1/UH-1	Cycle AV-8B and AH-1/UH-1 Launches until total assets used	AV-8B & AH-1/UH-1 unable launch/land at same time, 20min between
4	CH-53	AH-1/UH1	KC-130	MV-22B	AH-1/UH-1	F-35B	AH-1/UH-1	Cycle F-35B and AH-1/UH-1 Launches until total assets used	F-35B & AH-1/UH-1 unable launch/land at same time, 20 min between
5	LCAC	CH-53	KC-130	MV-22B				CH-53/MV-22B's Cycle until all assets are ashore	
6	LCAC	CH-53	KC-130	MV-22B				CH-53/MV-22B's Cycle until all assets are ashore	

The target engagement column, specified in Table 21, defines which red force target was the priority and which blue force asset available was prioritized to target a specific threat. This was based on inputs from the weapons experts and gave the simulation a realistic order of operations in the prosecution of a threat. To capture realistic execution, the 2S6 and SA-18 threats were treated as prohibitive. They must be destroyed before other targets were pursued due to their high threat to blue forces.

Table 21. CAS Asset to Target Priority

Target	Overall Priority	Target Engagement	
2S6	1	F-35B/AV-8B	
SA-18	2	AV-8B/F-35B	
120mm Mortar	3	AH-1/UH-1	AV-8B/F-35B
60mm Mortar	4	AH-1/UH-1	AV-8B/F-35B
T-72	5	AV-8B/F-35B	AH-1/UH-1
BMP-2	6	AH-1/UH-1	F-35B/AV-8B
BRDM	7	AV-8B/F-35B	AH-1/UH-1
Trucks	8	AH-1/UH-1	F-35B/AV-8B
Insurgents	9	AH-1/UH-1	F-35B/AV-8B

In addition to asset to target priority, a weapon to target priority was also defined in order to capture battlefield weaponeering. The weapon to target match was determined by a combination of the inferred probability of desired effect, and the platform employing the weapon. Weapons and Tactics Instructors (WTI), who are graduates of the course in Yuma, AZ, provided these preferences without providing weapons specific numbers to maintain an unclassified report. Table 22 defines the priority of each weapon being used on a specific target. The prioritization of weapons used was an input into the CAS model. From here, the weapon probability of desired effect in Table 14 was used to determine success of an attack.

Table 22. Weapon to Target Priority

		Target							
Weapon	2S6	SA-18	120mm Mortar	60mm Mortar	T-72	BMP-2	BRDM	Trucks	Insurgents
M483A1					6				
M795		1	9	9		7	8	7	1
M982	1								
M1101		2	3	3					
GBU-12	6	4	6	6	2	4	3	4	9
GBU-32 VT	3	6	7	7					5
GBU-38 VT	5	7	8	8					6
GBU-53/B	4	5	5	5	3		2		10
GBU-54	2	3	4	4	1	3	1	3	4
M197						5	6	5	3
M229						6	7	6	2
APKWS			2	2	5	2	5	2	8
AGM-114K2A			1	1	4	1	4	1	7

All independent variables were evaluated via the individualized scenarios identified by the experimental design that are discussed in the remaining chapters. A sample of individual runs with the variables adjusted as part of the customized design of experiments is shown in Table 23.

Table 23. Sample Simulation Run Test Variables

Run Number	Aircraft Type	Load out	Temperature	Sea State	Clouds	Ship2Shore Dist	Total Asset Qty	Assets per Launch	Threat
1	F-35B	Opt1	Hot	Choppy	Clear	Far	High	Average	Low
2	F-35B	Opt1	Average	Choppy	Low	Average	High	Low	Low
3	AV-8B	Opt2	Cold	Choppy	Clear	Average	Average	High	High
4	F-35B	Opt1	Average	Rough	Low	Far	High	High	Med
5	AV-8B	Opt1	Hot	Rough	Low	Average	Average	Average	High
6	AV-8B	Opt2	Cold	Rough	Clear	Far	High	High	Low
7	AV-8B	Opt1	Hot	Choppy	Clear	Near	Average	Low	High
8	AV-8B	Opt1	Hot	Rough	Mid	Near	High	High	High
9	F-35B	Opt2	Average	Calm	Clear	Near	Low	Low	Low
10	F-35B	Opt1	Average	Rough	Clear	Far	Low	High	High
11	F-35B	Opt2	Cold	Calm	Mid	Average	Low	Low	Low
--	--	--	--	--	--	--	--	--	--
136	AV-8B	Opt1	Hot	Choppy	Low	Far	Average	High	Low

4. GCS Model Inputs

The inputs and outputs for the GCS model were stored in Excel spreadsheets. The data that was used as inputs were:

- independent variables captured as variation in asset quantities or type, variation in fuel consumption, variation in probability of desired effect, or variation in probability of neutralization
- fuel consumption rates of assets
- red force threat level structure
- asset to target priorities
- weapon to target priorities
- probabilities of desired effect
- probabilities of neutralization
- asset speed

The model inputs that were independent variables are shown in Table 24 and Table 25. There were ten independent variables, or factors: environmental variables (temperature, sea state, red force threat level, and shore-to-firing distance), type of artillery asset, weapon loadout, total weapons quantity, transit medium, quantity of transit mediums per launch, and distance from ship to shore. Similar to the CAS model inputs, the GCS model inputs consisted of environmental independent variables and decision independent variables as noted in the previous chapter. Additional information that was inputted to the GCS model was a look up table or normal distribution of values for: priority of which weapon used to neutralize a target, probability of neutralizing red force targets with a given blue force weapon, and probability of blue force asset neutralization. The model inputs were based on stakeholder input on assets of interest and team member experience on doctrine.

Environmental conditions such as temperature, sea state, red force structure, and shore-to-firing distance were considered as inputs to the model and are shown in Table 24. The environmental conditions were shown as ranges, and were incorporated into the model by adjusting asset fuel consumption, weapon effectiveness, or probability of neutralization accordingly. These environmental conditions were similar to the CAS model, with the exception of removing cloud cover as a factor and adding shore-to-firing distance as a factor. The sea state was defined as wave height in order to more closely

align with the specifications for the LCAC outlined in the operational manual (Naval Doctrine Command 1997).

Table 24. GCS Environmental Conditions Independent Variables

Environmental Independent Variable	Options	Metric	Range
Weather	Cold	Temp (˚F)	< 40
	Average		> 40 , < 80
	Hot		> 80
Sea State	Calm	Wave Height (feet)	< 1
	Choppy		> 1 , < 8
	Rough		> 8
Red Force Threat Level	Low	Type of Assets	See Table 16
	Medium		
	High		
Shore to Firing Position Distance	Near	Miles	5
	Average		15
	Far		30

The shore to firing position distance was developed from doctrine execution of ship to shore movement by an MEU with an offload of assets on the beach, which resulted in relatively close ship to firing distances. The logistical stretch of the MEU is not designed to extend far ashore, thus near, average and far ranges were identified that fell within the MEU capability (*Expeditionary Force 21* 2014a).

There were six decision independent variables that were varied to represent DOTMLPF adjustments in a GCS scenario. The six decision independent variables for the GCS model are shown in Table 25.

Table 25. GCS Decision Independent Variables

Decision Independent Variable	Options (Physical Traceability)	Metric	Range	Functional Traceability
Type of Artillery	Howitzer	--	--	1.3.1 Conduct Indirect Fires
	EFSS		--	
	Howitzer + EFSS		--	
Weapon Loadout	Conventional	Weapon Type	See Table 15	1.3.1 Conduct Indirect Fires
	Precision			
Total Weapons Quantity	Low	Number of Tubes	Howitzer:2 EFSS:2	1.3.1 Conduct Indirect Fires
	Average		Howitzer: 4 EFSS: 4	
	High		Howitzer: 6 EFSS: 8	
Transit Medium	Air	Type	--	1.1 Conduct Assault Support
	Sea		--	
Quantity of Transit Mediums per Launch	Low	Number of Transit (Air or Sea) Mediums	3	1.1 Conduct Assault Support and 1.1 Conduct Assault Support
	Average		6	
	High		9	
Distance to Shore	Near	Nautical Miles	10	1.3.1 Conduct Indirect Fires and 1.1 Conduct Assault Support
	Average		75	
	Far		150	

Total weapons quantity alters the total number of tubes analyzed in order to identify potential changes to doctrine. The MEU commonly takes 4 EFSS assets and 4 M777A2 assets. Eight tubes were used for the high total weapons quantity of the EFSS and 6 tubes were used for the high total weapons quantity of the M777A2, which was based on traditional mortar employment.

The transit medium was determined to either be by air or sea. When sea transport was chosen, the platform used was the LCAC and when air transport was chosen, an MV-22 or CH-53K was used. The LCAC was used based on current load out assignments for an MEU. The doctrinal employment of the EFSS is to be internally transported by the MV-22. Due to this, the M777A2 was transported by the CH-53K. Both methods of air transport used a mix of UH-1Ys and AH-1Zs as escort assets.

The ship to shore distances differ from the CAS distances primarily due to the LCACs because rotors cannot extend to the ranges outlined in the CAS model. Traditional employment of ship to shore connectors is between 8–10 nautical miles off shore. 150 nautical miles is used as the far distance to simulate the USMC's goal of placing ships further off shore and out of enemy threat rings (*Expeditionary Force 21* 2014a).

The remaining GCS input values that have not been documented in previous chapters are described in this section. The GCS loading plan was a model input that influenced the total mission time and the total artillery assets per transit. The loading plan for the EFSS is shown in Table 26. The loading plan identified the number of air and sea assets needed to transport a given number of EFSS assets. A low number could require the transport asset to make multiple trips to deliver the weapon systems. It also identified the times for embarking and debarking as well as the quantity of ammunition that was carried.

Table 26. EFSS Loading Plan

# EFSS	# MV-22B	# LCAC	Embark (min)	Debark (min)	Ammo Qty	Comments
2	6		20	15	68	(2) weapon prime movers, (2) ammo prime movers, (2) light strike vehicles
4	12		30	25	136	(4) weapon prime movers, (4) ammo prime movers, (4) light strike vehicles
8	21		40	35	272	(8) weapon prime movers, (8) ammo prime movers, (5) light strike vehicles
2		1	30	15	68	(2) weapon prime movers, (2) ammo prime movers, (2) light strike vehicles
4		1	40	25	136	(4) weapon prime movers, (4) ammo prime movers, (4) light strike vehicles
8		2	50	35	272	(8) weapon prime movers, (8) ammo prime movers, (5) light strike vehicles

The loading plan for the M777A2 was extracted from the MAGTF Planner's Reference Manual (MSTP 2012) and is shown in Table 27. The loading plan shows the quantity of air and sea assets needed to transport a given number of howitzers.

Table 27. M777A2 Loading Plan (from MSTP 2012)

# M777A2	# CH-53K	# LCAC	Embark (min)	Debark (min)	Ammo Qty	Comments
2	4		20	15	48	(2) howitzers, (2) HMMWV
4	7		30	25	96	(4) howitzers, (3) HMMWV
6	10		40	35	144	(6) howitzers, (4) HMMWV
2		2	30	25	208	(2) howitzers, (2) MTVR, (2) HMMWV
4		4	60	55	416	(4) howitzers, (5) MTVR, (3) HMMWV
6		7	90	85	624	(6) howitzers, (9) MTVR, (3) HMMWV

5. Model Outputs

The outputs of the simulation runs were exported from ExtendSim into an Excel file. Table 28 identifies the model outputs that indicate the operational effectiveness of the MEU. Table 29 identifies the model outputs that indicate fuel consumption metrics of the MEU.

Table 28. Operational Effectiveness Model Outputs

Red Force Target Neutralization
Munitions Expenditure
Blue Force Assets Destroyed
Total Mission Time

Table 29. Fuel Consumption Outputs

Output Term	**Output Definitions**
PlatformID	Unique ID of the platform
Total Fuel	Total fuel use of the asset
Total Time	Total mission time of the asset
STTO Time	Total time the air asset spends in the STTO and Transit phase of the mission
STTO Fuel	Total fuel the air asset used in the STTO and Transit phase of the mission
CAS Fuel	Fuel an air asset uses while loitering during the Conduct Mission phase
Refuel Fuel	Fuel an air asset uses while on a refueling mission.
KCFWFuelXfer	Fuel transferred from the KC-130 to the air asset
RTB Fuel	Fuel an air asset used during the Return To Base phase.
TransitToEngagement Fuel	Fuel used by a transport asset transporting ground assets from ship-to-shore, ship-to-mission-area, or shore-to-mission-area in the GCS model
TransitToEngagement Time	Time a transport asset spends transporting ground assets from ship-to-shore, ship-to-mission-area, or shore-to-mission-area in the GCS model
TransitFromEngagement Fuel	Fuel used by a transport asset transporting ground assets from shore-to-ship, mission-area-to-ship, or mission-area-to-shore in the GCS model
TransitFromEngagement Time	Time a transport asset spends transporting ground assets from shore-to-ship, mission-area-to-ship, or mission-area-to-shore in the GCS model
Engagement Time	Total engagement time of the GCS model

6. Casualty Modeling

Air asset casualties are modeled using probability of hit, probability of detection, and survivability. Blue force air asset casualties depends on the probability that the air asset is detected, the probability of hit based on the red forces weapon, and the survivability of the air asset against the red force weapon. System boundary limitations reduce the accuracy of casualty modeling due to F-35B probability of detection data being classified. Ground asset casualties are modeled using probability of hit, damage radius, and survivability, blue force ground asset casualties depend on the survivability against a red force of a particular size. Red force ground asset casualties depend on the

blue force air asset probability of hit, damage radius, survivability against blue force air asset weapon, survivability against blue force artillery, and survivability against a blue force of a particular size.

B. SYSTEM VERIFICATION

With a functioning model the verification of the behavior of the physical components of the MEU was verified in ExtendSim. The MEU was verified when all requirements from step 3 were met during the simulation run. Due to environmental constraints, not all requirements from step 3 were met. As discussed in Future Research, GCE employment is a recommend project for future teams. Blue force casualties could not be accurately simulated due to classification restrictions. Due to the discreet nature of ExtendSim, capturing accurate time to mission completion and a reactive red-force proved to require more time than environmental constraints allowed.

C. SUMMARY

The system behavior was verified to meet the requirements of fuel and weapons expenditure as well as red force percent of neutralization. Using these metrics, DOTMPLF recommendations with respect to doctrine and materiel were made to adjust fuel usage without sacrificing operational effectiveness.

VI. VERIFY PERFORMANCE

Step six and seven of the tailored-SE Vee focused on verification of the components and system developed. In these steps, the process used to bring the methodology together and identify fuel usage efficiencies and operational effectiveness in the context of an MEU operation was documented. The overall approach taken was to use a DOE strategy to efficiently identify factors or factor interactions that generated the most impact or had the largest effect on fuel efficiency and operational effectiveness in the context of MEU operation. Once those factors were identified, a regression fit was developed and used to predict the fuel efficiency and operational effectiveness of the MEU operation and to identify the best combination of fuel usage and operational effectiveness. The results provided at this step represent the capability originally required by the stakeholders and essentially documents the verified system operational architecture.

A. DESIGN OF EXPERIMENT

The use of DOE or statistical design originated with agricultural experiments conducted in the 1920's and soon spread to the manufacturing industry. Early researchers recognized that the way tests were conducted often affected their ability to analyze the resulting data (Montgomery 2009). The methods developed by these early researchers were used to produce low-order mathematical equations that a) quantified how well the system under test performed, b) identified the interaction between input variables, and c) identified which input variables were most important. The use of DOE has continued to increase as a part of commercial industry practices, especially as a component of quality assurance programs. DOE "can also be successfully applied to computer simulation [models] of [real] physical systems" (Montgomery 2009). The data from the simulation model in these applications is used to develop a metamodel, which is then used to understand or optimize the simulation model. The assumption made was that if the simulation model was a reasonable representation of the real physical system, then

decisions made or optimization using the metamodel would produce adequate results for the real system.

Using the ExtendSim simulation model of the MEU operation described above, a metamodel was developed in order to a) identify which factor or factor interaction had the largest impact or effect on each MOP, b) develop a figure of merit (FOM) to identify a dominant combination of fuel usage (MOP 1) with the other operational aspects of an MEU (MOP 3 through 8), and c) identify the best combination of fuel usage and operational effectiveness in terms of an overall FOM (OFOM).

The metamodel for each MOP was originally to be constructed using a full, three level (3^k) factorial DOE strategy. Unfortunately, this DOE strategy required 19,683 ExtendSim simulation model runs for each metamodel, far more than could be accomplished in a reasonable amount of time given the complexity of the ExtendSim simulation model developed. Instead, a custom DOE strategy was developed using the JMP Pro V12 software package that provided a similar capability, but required significantly fewer ExtendSim simulation model runs for each metamodel.

B. CAS ANALYSIS

For the CAS analysis, metamodels were developed using nine independent variables, each selected as potentially having a significant effect on either fuel efficiency or operational effectiveness. The results of the CAS analysis performed are described below.

1. Custom DOE Strategy Setup

Development of the metamodel was based on a custom DOE strategy using the nine categorical factors shown in Table 30. Also shown was the factor name for each variable and the available values for each factor. A custom design DOE strategy was selected, which required 136 ExtendSim simulation model runs for these nine factors. For each of these 136 model runs, the value selected for each factor is shown in Appendix C.

Table 30. CAS DOE Factors and Values

Variable	Factor Name	First Value	Second Value	Third Value
Type of Aircraft	Aircraft Type	AV-8B	F-35B	Not Used
Weapon Loadout	Loadout	Option 1 (current doctrinal weapon load out)	Option 2 (future doctrinal weapon load out)	Not Used
Weather	Temperature	Cold (< 40 F)	Average (> 40, < 80 F)	Hot (> 80 F)
Sea State	SeaState	Rough (< 1 ft)	Choppy (> 1 ft, < 8 ft)	Calm (> 8 ft)
Cloud Cover	Clouds	Low (< 5k ft)	Mid (< 25k ft, > 5k ft)	Clear (> 25k ft)
Distance to Shore	Ship2Shore Dist	Far (300 NM)	Average (100 NM)	Near (60 NM)
Number of Total Assets Per Type	Total Asset Qty	Low (< 80%)	Average (> 80%, < 115%)	High (> 115%)
Number of Assets Per Launch	Assets per Launch	Low (<50%)	Average (>50%, <150%)	High (>150%)
Red Force Threat Level	Threat	Low	Medium	High

2. Metamodel Development — CAS Function 1.2.1

Using the DOE strategy described above, a metamodel was developed to predict the MOPs identified in Table 3 for the CAS function. The CAS#1 Metamodel *Total Fuel Used* was developed for MOP 1 and predicted the total fuel used in gallons during the MEU simulation. The CAS #3 Metamodel *Average Mission Time* was developed for MOP 3 and predicted the average mission time in minutes for the MEU simulation. The CAS #4 Metamodel *Targets Neutralized* was developed for MOP 4 and predicted the average number of targets neutralized in percent during the MEU simulation. The CAS #6 Metamodel *Blue Casualty* was developed for MOP 5 and predicted the average number of blue force assets destroyed in percent during the MEU simulation. The CAS

#9 Metamodel *Mission Success* was developed using results from CAS Metamodels #3, #4 and #6 and predicted the mission success percentage of the CAS mission of the MEU operation. The specific model for each MOP was summarized in Table 31.

Table 31. CAS Metamodels Developed

CAS Metamodel	Units	CAS MOP Predicted
CAS #1 Total Fuel Used	gallons	MOP 1: Fuel consumption
CAS #3 Average Mission Time	minutes	MOP 3: Length of mission (time)
CAS #4 Target Neutralized	percent	MOP 4: Number of targets neutralized
CAS #6 Blue Casualty	percent	MOP 5: Number of Blue Force assets destroyed
CAS #9 Mission Success	percent	Overall performance of MOP 3,4, and 5

a. *CAS #1 Metamodel Total Fuel Used*

Using the DOE strategy presented earlier, 136 ExtendSim simulation model runs were conducted and the total fuel used from each simulation model run recorded. Regression analysis was then conducted and a metamodel was developed to predict total fuel used (as gallons) during the MEU operation. Figure 17 presents an evaluation of this metamodel and suggests that the prediction equation fits the data well. Numerically, the R^2 value of 0.999 confirms that the CAS #1 Metamodel *Total Fuel Used* was an excellent fit to the ExtendSim simulation model as shown in Table 32.

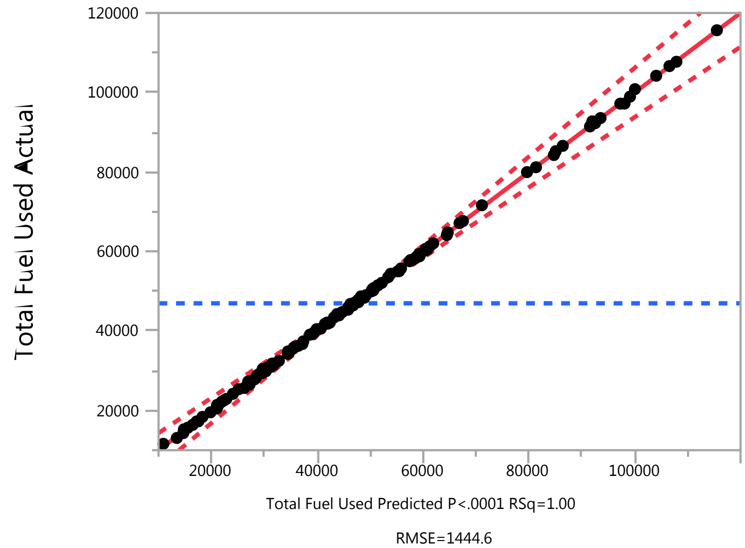

Figure 17. CAS #1 Metamodel *Total Fuel Used* (gal)

Table 32. CAS #1 Metamodel *Total Fuel Used* (gal) Regression Diagnostics

RSquare	0.999829
RSquare Adj	0.996154
Root Mean Square Error	1444.579
Mean of Response	46953.27

b. CAS #3 Metamodel Average Mission Time

Using the DOE strategy presented earlier, 136 ExtendSim simulation model runs were conducted and the average mission time from each simulation model run recorded. Regression analysis was then conducted and a metamodel was developed to predict average mission time (in minutes) during the MEU operation. Figure 18 presents an evaluation of this metamodel and suggests that the prediction equation fits the data well. Numerically, the R^2 value of 0.994 confirms that the CAS #3 Metamodel *Average Mission Time* was an excellent fit to the ExtendSim simulation model as shown in Table 33.

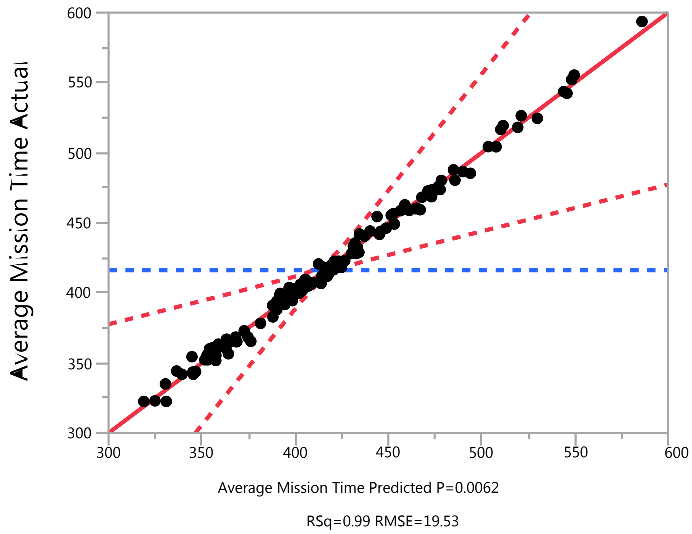

Figure 18. CAS #3 Metamodel *Average Mission Time* (minutes)

Table 33. CAS #3 Metamodel *Average Mission Time* (minutes) Regression Diagnostics

RSquare	0.99444
RSquare Adj	0.874892
Root Mean Square Error	19.52992
Mean of Response	416.1169
Observations (or Sum Wgts)	136

c. CAS #4 Metamodel Targets Neutralized

Using the DOE strategy presented earlier, 136 ExtendSim simulation model runs were conducted and the percentage of targets neutralized from each simulation model run recorded. Regression analysis was then conducted and a metamodel was developed to predict targets neutralized (as a percentage of original targets) during the MEU operation. Figure 19 presents an evaluation of this metamodel and suggests that the prediction equation fits the data well. Numerically, the R^2 value of 0.994 confirms that the CAS #4 Metamodel *Targets Neutralized* was an excellent fit to the ExtendSim simulation model as shown in Table 34.

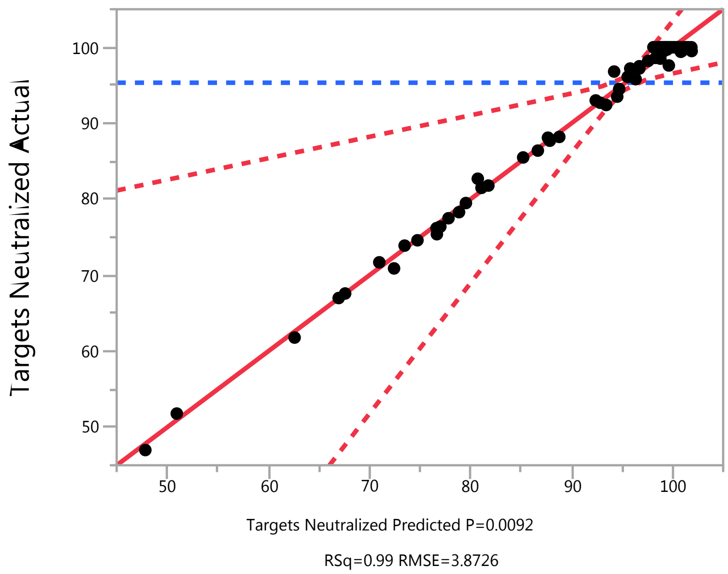

Figure 19. CAS #4 Metamodel *Targets Neutralized* (%)

Table 34. CAS #4 Metamodel *Targets Neutralized* (%) Regression Diagnostics

RSquare	0.993564
RSquare Adj	0.8552
Root Mean Square Error	3.872598
Mean of Response	95.33309
Observations (or Sum Wgts)	136

d. CAS #6 Metamodel Blue Casualty

Using the DOE strategy presented earlier, 136 ExtendSim simulation model runs were conducted and the blue force casualties from each simulation model run recorded. Regression analysis was then conducted and a metamodel was developed to predict blue force assets destroyed (as percentage of the original force) during the MEU operation. Figure 20 presents an evaluation of this metamodel and suggests that the prediction equation fits the data well. Numerically, the R^2 value of 0.972 confirms that the CAS #6 Metamodel *Blue Casualty* was an excellent fit to the ExtendSim simulation model as shown in Table 35.

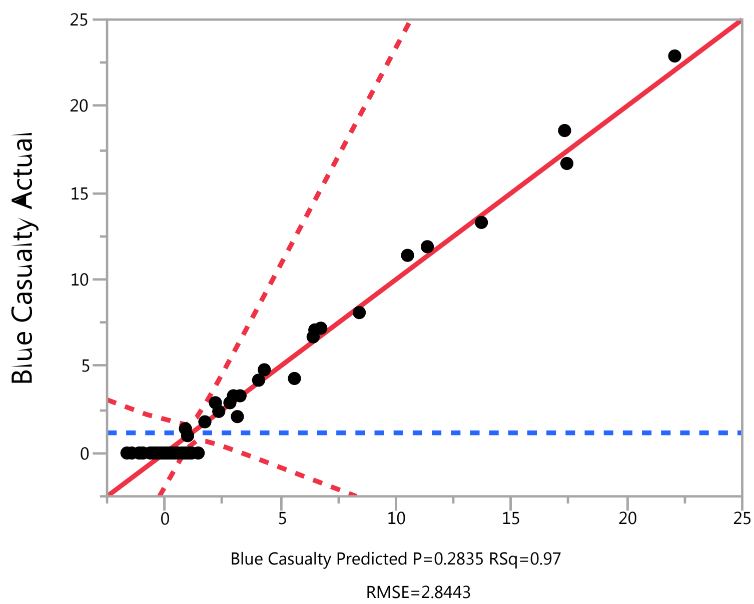

Figure 20. CAS #6 Metamodel *Blue Casualty*

Table 35. CAS #6 Metamodel *Blue Casualty* Regression Diagnostics

RSquare	0.972108
RSquare Adj	0.372436
Root Mean Square Error	2.844336
Mean of Response	1.163971
Observations (or Sum Wgts)	136

e. CAS #9 Metamodel Mission Success

Using the DOE strategy presented earlier, 136 ExtendSim simulation model runs were conducted and the mission success from each simulation model run recorded. Regression analysis was then conducted and a metamodel was developed to predict the mission success during the MEU operation. Figure 21 presents an evaluation of this metamodel and suggests that the prediction equation fits the data well. Numerically, the R^2 value of 0.981 confirms that the CAS #9 Metamodel *Mission Success* was an excellent fit to the ExtendSim simulation model as shown in Table 36.

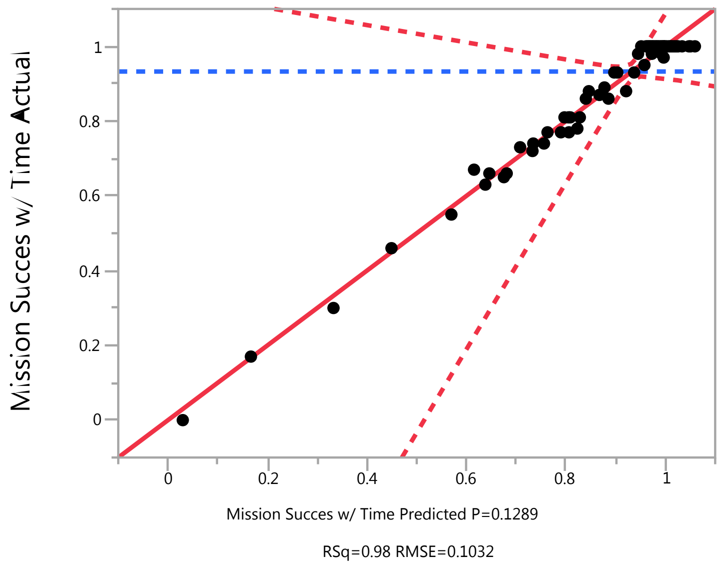

Figure 21. CAS #9 Metamodel *Mission Success*

Table 36. CAS #9 Metamodel *Mission Success* Regression Diagnostics

RSquare	0.981272
RSquare Adj	0.578623
Root Mean Square Error	0.10322
Mean of Response	0.932574
Observations (or Sum Wgts)	136

3. Metamodel Prediction — Overall Factor Effect and Desirability Analysis

Each MOP was evaluated in more detail using factor plots. These plots are particularly useful for visualizing the impact that each factor has on each MOP. Further, desirability can be defined for each MOP and preferred system configurations can be identified based on the analysis. The best desired response, or desirability value, ranged from 0 to 1 and the value selected based on the particular MOP.

a. *CAS #1 Metamodel Prediction — Overall Factor Effect and Desirability*

For the CAS #1 Metamodel Total Fuel Used, a desirability value of 1 was assigned to the lowest predicted total fuel used per MEU operation. The curves in Figure 22 visually present the impact that each factor has on the MOP (where steeper slopes are associated with factors that have a more substantial impact on the MOP). It also shows the specific selection of factor values that maximized the desirability function (in this case, resulted in the lowest fuel consumption).

As shown, the lowest value of total fuel used was 26,657 gallons for the MEU operation. The factor Total Asset Qty generated the largest delta in total fuel used. Total fuel used significantly decreased when going from the (high) value of 115% of current doctrine to the (low) value of 80% of doctrine. Both Ship2Shore Dist and Assets per Launch were next in terms of effecting total fuel used. A decrease in total fuel used was clearly evident when the factor Ship2Shore Dist decreased from the (far) distance of 300 NM to the (near) distance of 60 NM, as well as when the factor Assets per Launch decreased from the (high) value of 150% of doctrine to 50% of doctrine.

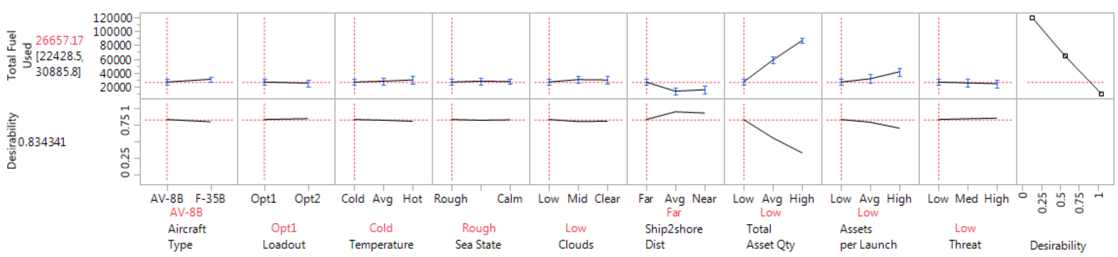

Figure 22. CAS#1 Metamodel *Total Fuel Used* Desirability

b. *CAS #3 Metamodel Prediction — Overall Factor Effect and Desirability*

For the CAS #3 Metamodel *Average Mission Time*, a desirability value of 1 was assigned to the lowest predicted mission time per MEU operation. This was based on the assumption that the quicker a mission was completed, the less negative impact there would be on fuel used and potential casualties. The curves in Figure 23 illustrate the sensitivity associated with each factor on the predicted metamodel response. It also

shows the specific selection of factor values that maximized the desirability of the lowest possible average mission time for the MEU operation.

As shown, the lowest average mission time was predicted to be 366 minutes. Several of the nine factors had some effect on minimizing the average mission time the for the MEU operation. Of particular note was the effect of the factor Loadout, where going from the (Opt2) value of a larger quantity of onboard weapons to the (Opt1) value of having fewer onboard weapons resulted in a reduction in overall mission time. The factor Aircraft Type also slightly reduce average mission time when going from the AV-8B to the F-35B aircraft, most likely due to the ability of the F-35B to reach the enemy target quicker. The factor Total Asset Qty at the (average) value of <80% to <115% of current doctrine increased average mission time, while the weather factor clouds at the (low) value of overcast (< 5000 ft elevation) decreased the average mission time of the MEU operation.

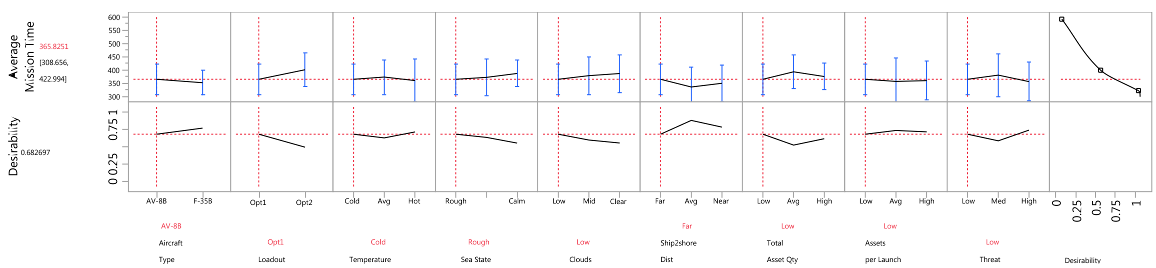

Figure 23. CAS #3 Metamodel *Average Mission Time* Desirability

c. *CAS #4 Metamodel Prediction — Overall Factor Effect and Desirability*

For the CAS #4 Metamodel *Targets Neutralized*, a desirability value of 1 was assigned to the highest predicted percentage of targets neutralized during the MEU operation. The curves in Figure 24 illustrate the sensitivity associated with each factor on the predicted metamodel response. It also shows the specific selection of factor values that maximized the desirability of the highest percentage of targets neutralized during the MEU operation.

As shown, the highest percentage of targets neutralized was 91.7%. Several of the nine factors had a significant effect on maximizing the percentage of targets neutralized

during the MEU operation. Of particular note was the effect of the factor Threat, where going from the (low) threat value associated with a more benign threat to the (high) threat value associated with a more sophisticated threat resulted in a significant reduction in percentage of targets neutralized. Also, the effect of the factor Loadout, where going from the (Opt2) value of a larger quantity of onboard weapons to the (Opt1) value of having fewer onboard weapons resulted in a reduction in the percentage of targets neutralized.

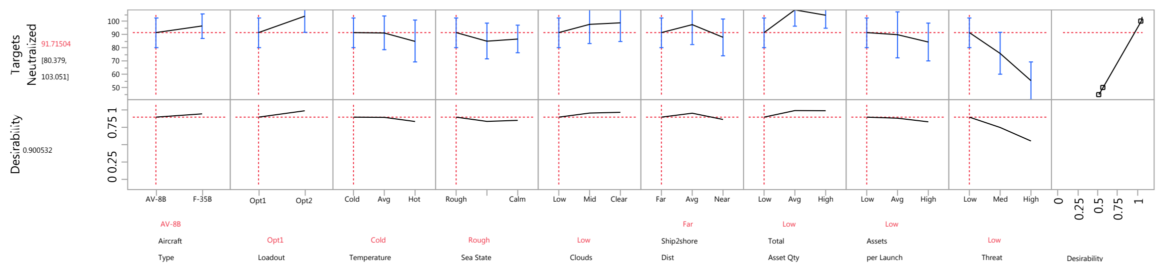

Figure 24. CAS #4 Metamodel *Targets Neutralized* Desirability

d. *CAS #6 Metamodel Prediction — Overall Factor Effect and Desirability*

For the CAS #6 Metamodel *Blue Casualty*, a desirability value of 1 was assigned to the lowest percentage of blue force assets destroyed during the MEU operation. The curves in Figure 25 illustrate the sensitivity associated with each factor on the predicted metamodel response. It also shows the specific selection of factor values that maximized the desirability of the lowest percentage of blue force assets destroyed during the MEU operation.

As shown, the lowest percentage of blue force assets destroyed was 3.24 %. Several of the nine factors had an effect on minimizing the percentage of blue force assets destroyed during the MEU operation. Of particular note was the effect of the factor Threat, where going from the (low) threat value associated with a more benign threat to the (high) threat value associated with a more sophisticated threat resulted in a significant increase in the percentage of blue force assets destroyed. Also, the effect of the factor Ship2Shore Dist, which had the best effect on percentage of blue force assets destroyed when at the (average) value of 100 NM. The factor Aircraft Type also slightly reduced

the percentage of blue force assets destroyed when going from the AV-8B to the F-35B aircraft. Also, the factor total asset quantity at the (average) value of <80% to <115% of current doctrine generated the best effect on percentage of blue force assets destroyed during the MEU operation.

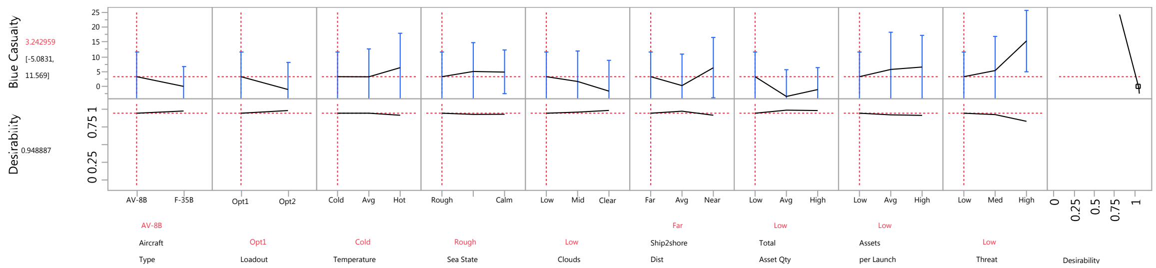

Figure 25. CAS #6 Metamodel *Blue Casualty* Desirability

e. CAS #9 Metamodel Prediction — Overall Factor Effect and Desirability

For the CAS #9 Metamodel *Mission Success*, a desirability value of 1 was assigned to the highest predicted mission success of the MEU operation. The curves in Figure 26 illustrate the sensitivity associated with each factor on the predicted metamodel response. It also shows the specific selection of factor values that maximized the desirability of the highest mission success of the MEU operation.

As shown, several of the nine factors had a significant effect on maximizing mission success of the MEU operation. Of particular note was the positive effect of the factor Aircraft Type at the (F-35B) value, Loadout at the (Opt1) value of current doctrine, and Total Asset Qty at the (high) value of 115% of current doctrine. There was also the negative effect on mission success by the factors Assets per Launch at the (high) value of 150% of current doctrine and the factor Threat at the (high) threat value.

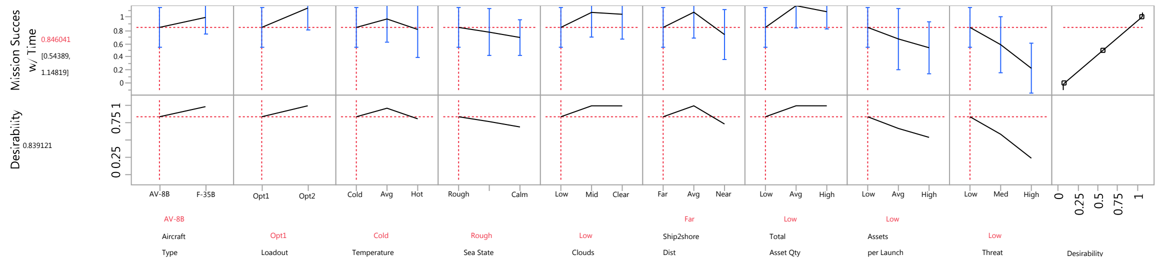

Figure 26. CAS #9 Metamodel *Mission Success* Desirability

4. Metamodel Factor Analysis

For each metamodel developed, an analysis was conducted in order to a) identify which metamodel factor or factor interaction had the largest impact on each MOP, b) identify the most significant interactions between MOPs, and c) identify the best combination of fuel usage and operational effectiveness in terms of the MOPs identified. The results of this analysis, contained in Appendix E, was used to prioritize the hundred plus factors initially produced by the DOE linear regression, down to a manageable level for consideration with the following efficient frontier analysis.

5. Metamodel Figure of Merit — Efficient Frontier Analysis

A FOM was calculated for each of the top ten factors or factor interactions that had the largest impact on the response predicted from each of the four metamodels developed. If they were not part of the top ten, FOMs were also calculated for the main factors that addressed DOTMLPF changes, i.e. Aircraft Type, Total Asset Qty, Assets per Launch, and Ship2Shore Dist. Using the FOMs calculated from the CAS #1 Metamodel *Total Fuel Used*, an efficient frontier plot was generated comparing these FOMs to those generated for the same factors or factor interactions from the other three CAS metamodels.

a. CAS #1 Metamodel Total Fuel Used FOM

For the CAS #1 metamodel *Total Fuel Used*, a FOM was calculated for each of the top ten factors or factor interactions that had the largest impact on the total fuel used during the MEU operation. This FOM was obtained by dividing the factor value or factor interaction value by the intercept value of 47,020 gallons. The FOM for each of the top

ten factors or factor interactions are shown in Table 37. Also shown in the table were those FOMs, if not part of the top ten, for the main factors that addressed DOTMLPF changes.

Table 37. CAS #1 Metamodel *Total Fuel Used* — FOM

Factor or Factor Interaction Used	CAS #1 FOM
Ship2Shore Dist[Far]	0.4841
Total Asset Qty[High]	0.4137
Total Asset Qty[Low]	-0.4017
Ship2Shore Dist[Near]	-0.2998
Ship2Shore Dist[Far]*Total Asset Qty[Low]	-0.2199
Ship2Shore Dist[Far]*Total Asset Qty[High]	0.2123
Ship2Shore Dist[Avg]	-0.1843
Total Asset Qty[High]*Assets per Launch[High]	-0.1574
Ship2Shore Dist[Near]*Total Asset Qty[Low]	0.1382
Ship2Shore Dist[Near]*Total Asset Qty[High]	-0.1304
Assets per Launch[Low]	-0.0903
Assets per Launch[High]	0.0837
Aircraft Type[AV-8B]	-0.0513
Aircraft Type[F-35B]	0.0513
Loadout[Opt2]	0.0228
Loadout[Opt1]	-0.0228
Total Asset Qty[Avg]	-0.0119
Assets per Launch[Avg]	0.0066

b. CAS #3 Metamodel Average Mission Time FOM

For the CAS #3 Metamodel *Average Mission Time*, a FOM was calculated for the exact same ten factors or factor interactions that had the largest impact on the total fuel used during the MEU operation. This FOM was obtained by dividing the factor value or factor interaction value by the interceptor. The FOM for each of the top ten factors or factor interactions are shown in Table 38. Also shown in the table were those FOMs, if not part of the top ten, for the main factors that addressed DOTMLPF changes.

Table 38. CAS #3 Metamodel *Average Mission Time* — FOM

Factor or Factor Interaction Used	CAS #3 FOM
Ship2Shore Dist[Far]	0.0060
Total Asset Qty[High]	0.0300
Total Asset Qty[Low]	-0.0572
Ship2Shore Dist[Near]	-0.0041
Ship2Shore Dist[Far]*Total Asset Qty[Low]	0.0075
Ship2Shore Dist[Far]*Total Asset Qty[High]	-0.0063
Ship2Shore Dist[Avg]	-0.0019
Total Asset Qty[High]*Assets per Launch[High]	-0.0020
Ship2Shore Dist[Near]*Total Asset Qty[Low]	0.0037
Ship2Shore Dist[Near]*Total Asset Qty[High]	0.0003
Assets per Launch[Low]	0.0847
Assets per Launch[High]	-0.0857
Aircraft Type[AV-8B]	-0.0294
Aircraft Type[F-35B]	0.0294
Loadout[Opt2]	0.0566
Loadout[Opt1]	-0.0566
Total Asset Qty[Avg]	0.0272
Assets per Launch[Avg]	0.0010

c. CAS #4 Metamodel Targets Neutralized FOM

For the CAS #4 Metamodel *Targets Neutralized*, a FOM was calculated for the exact same ten factors or factor interactions that had the largest impact on the total fuel used during the MEU operation. This FOM was obtained by dividing the factor value or factor interaction value by the interceptor. The FOM for each of the top ten factors or factor interactions are shown in Table 39. Also shown in the table were those FOMs, if not part of the top ten, for the main factors that addressed DOTMLPF changes.

Table 39. CAS #4 Metamodel *Targets Neutralized* —FOM

Factor or Factor Interaction Used	CAS #4 FOM
Ship2Shore Dist[Far]	0.0154
Total Asset Qty[High]	0.0020
Total Asset Qty[Low]	-0.0037
Ship2Shore Dist[Near]	-0.0140
Ship2Shore Dist[Far]*Total Asset Qty[Low]	-0.0124
Ship2Shore Dist[Far]*Total Asset Qty[High]	0.0062
Ship2Shore Dist[Avg]	0.0070
Total Asset Qty[High]*Assets per Launch[High]	0.0120
Ship2Shore Dist[Near]*Total Asset Qty[Low]	0.0151
Ship2Shore Dist[Near]*Total Asset Qty[High]	-0.0059
Assets per Launch[Low]	-0.0017
Assets per Launch[High]	0.0025
Aircraft Type[AV-8B]	0.0012
Aircraft Type[F-35B]	0.0049
Loadout[Opt2]	0.0006
Loadout[Opt1]	0.0029
Total Asset Qty[Avg]	-0.0002
Assets per Launch[Avg]	-0.0046

d. CAS #6 Metamodel Blue Casualty FOM

For the CAS #6 Metamodel *Blue Casualty*, a FOM was calculated for the exact same ten factors or factor interactions that had the largest impact on the total fuel used during the MEU operation. This FOM was obtained by dividing the factor value or factor interaction value by the interceptor. The FOM for each of the top ten factors or factor interactions are shown in Table 40. Also shown in the table were those FOMs, if not part of the top ten, for the main factors that addressed DOTMLPF changes.

Table 40. CAS #6 Metamodel *Blue Casualty* — FOM

Factor or Factor Interaction Used	CAS #6 FOM
Ship2Shore Dist[Far]	0.1865
Total Asset Qty[High]	-0.8223
Total Asset Qty[Low]	1.6554
Ship2Shore Dist[Near]	0.3533
Ship2Shore Dist[Far]*Total Asset Qty[Low]	0.1872
Ship2Shore Dist[Far]*Total Asset Qty[High]	0.6068
Ship2Shore Dist[Avg]	-0.5398
Total Asset Qty[High]*Assets per Launch[High]	-0.0568
Ship2Shore Dist[Near]*Total Asset Qty[Low]	-0.0563
Ship2Shore Dist[Near]*Total Asset Qty[High]	-0.6570
Assets per Launch[Low]	-0.1148
Assets per Launch[High]	-0.0679
Aircraft Type[AV-8B]	0.1996
Aircraft Type[F-35B]	-0.1996
Loadout[Opt2]	-0.4203
Loadout[Opt1]	0.4203
Total Asset Qty[Avg]	-0.8331
Assets per Launch[Avg]	0.1828

e. CAS #9 Metamodel Mission Success FOM

For the CAS #9 Metamodel *Mission Success*, a FOM was calculated for the exact same ten factors or factor interactions that had the largest impact on the total fuel used during the MEU operation. This FOM was obtained by dividing the factor value or factor interaction value by interceptor. The FOM for each of the top ten factors or factor interactions are shown in Table 41. Also shown in the table were those FOMs, if not part of the top ten, for the main factors that addressed DOTMLPF changes.

Table 41. CAS #9 Metamodel *Mission Success* — FOM

Factor or Factor Interaction Used	CAS #9 FOM
Ship2Shore Dist[Far]	-0.0082
Total Asset Qty[High]	0.0480
Total Asset Qty[Low]	-0.0886
Ship2Shore Dist[Near]	-0.0118
Ship2Shore Dist[Far]*Total Asset Qty[Low]	-0.0307
Ship2Shore Dist[Far]*Total Asset Qty[High]	-0.0251
Ship2Shore Dist[Avg]	0.0199
Total Asset Qty[High]*Assets per Launch[High]	0.0352
Ship2Shore Dist[Near]*Total Asset Qty[Low]	0.0140
Ship2Shore Dist[Near]*Total Asset Qty[High]	0.0333
Assets per Launch[Low]	-0.0215
Assets per Launch[High]	-0.0008
Aircraft Type[AV-8B]	0.0041
Aircraft Type[F-35B]	-0.0041
Loadout[Opt2]	0.0120
Loadout[Opt1]	-0.0120
Total Asset Qty[Avg]	0.0406
Assets per Launch[Avg]	0.0223

6. Metamodel FOM — CAS — MOP 1 Total Fuel used vs. MOP 3 Length of Mission — Efficient Frontier

Using the FOMs calculated from the CAS #1 Metamodel *Total Fuel Used* and from the CAS #3 Metamodel *Average Mission Time,* an efficient frontier plot was developed to identify the specific factor or factor interaction that would result in the best combination of MOP 1 – Fuel Consumption and MOP 3 – Length of Mission. Prior to developing the efficient frontier plot, each FOM was linearly scaled from 0 to 1, using the minimum and maximum FOM values. For the CAS #1 Metamodel *Total Fuel Used*, the largest negative value was considered best and assigned a value of 1. The largest positive value was considered worst and assigned a value of 0. For the CAS#3 Metamodel *Average Mission Time*, the largest negative value was considered best and

assigned a value of 1. The largest positive value was considered worst and assigned a value of 0.

Using the scaled FOM values, an efficient frontier plot was developed comparing the performance obtained in terms of total fuel used and average mission time using the ten factors or factor interactions that generated the largest effect on total fuel used during the MEU operation. If they were not part of the top ten, scaled FOMs for the main factors that addressed DOTMLPF changes, i.e. Aircraft Type, Total Asset Qty, Assets per Launch, and Ship2Shore Dist were also plotted on the efficient frontier plot. As shown in Figure 27, the factor Total Asset Qty at the (low) value of 80% of current doctrine dominated all other combinations. The factors Ship2Shore Dist at the (near) value of 60 NM, Assets per Launch at the (high) value of 150% of current doctrine, and Load Out at the (Opt1) value of current weapon doctrine were next in terms of dominating the remaining factors or factor interactions.

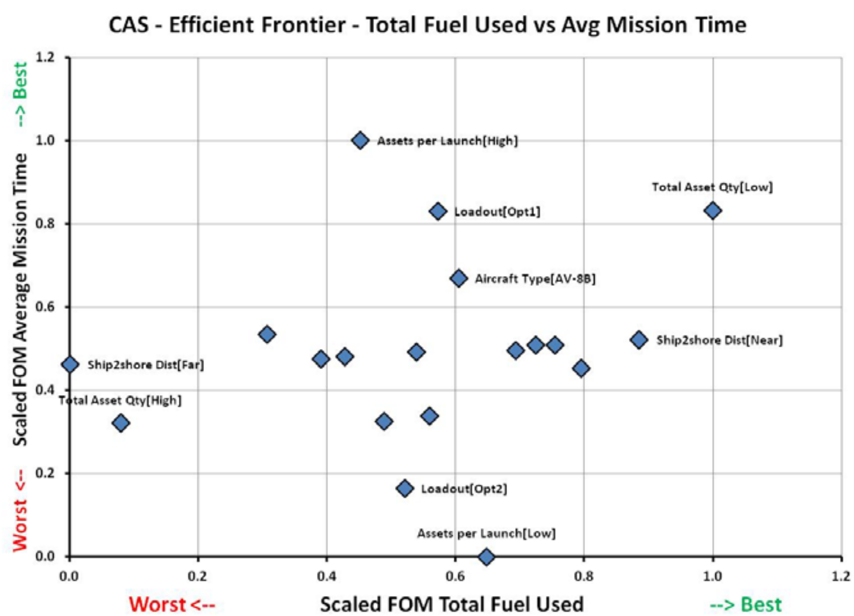

Figure 27. CAS — Efficient Frontier Plot — Total Fuel Used vs. Average Mission Time

Using these scaled FOM values, an OFOM was developed by calculating the straight line distance from each scaled FOM combination to the ideal scaled FOM value

of (1,1). This distance, with the shortest distance representing the better OFOM, was plotted in Figure 28 for all of the scaled FOM combinations. For example, the factor Total Asset Qty at the (Low) value was very close to the ideal condition (1,1) of generating the best scaled FOM for average mission time and the best scaled FOM for total fuel used. The magnitude of this distance, the OFOM, was calculated to be 0.167 and was the closest of any single factor or factor interaction. The next closest distance to the ideal of (1,1) was obtained with the factor Loadout at the (Opt1) value. In this case, the calculated OFOM was 0.461.

As shown in Figure 28, the factor Total Asset Qty at the (low) value of 80% was the closest to the ideal value of (1,1), providing the best combination of lowest total fuel used and shortest average mission time for the MEU operation. This was followed by the factor Loadout at the (Opt1) value of current weapon doctrine as the second best OFOM. The OFOM values obtained for several of the remaining factors or factor interactions were also shown in Figure 28.

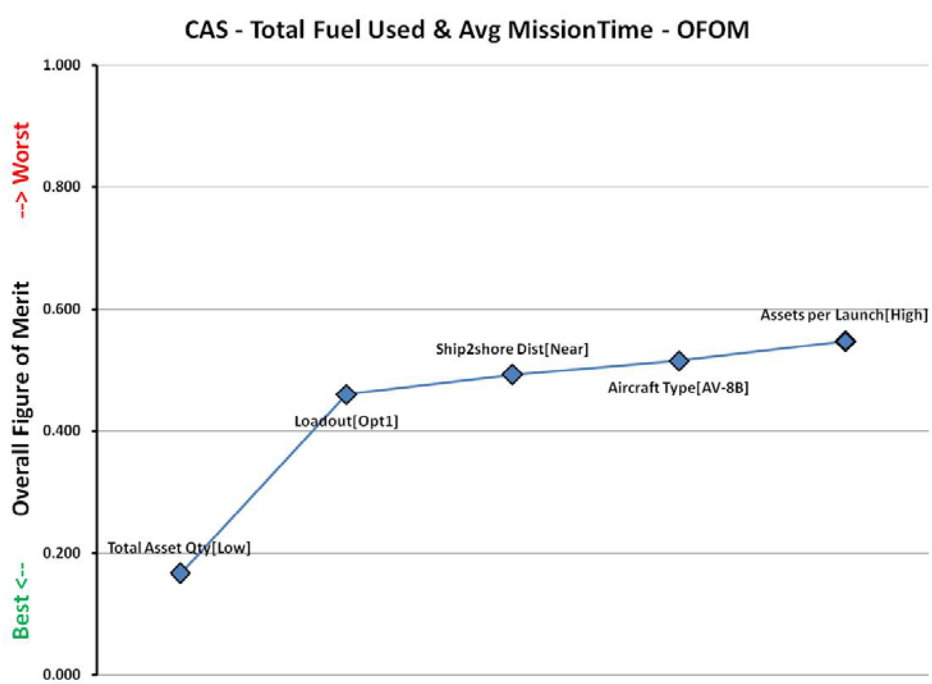

Figure 28. CAS — OFOM Ranking — Total Fuel Used vs. Average Mission Time

7. Metamodel FOM — CAS — MOP 1 Total Fuel used vs. MOP 4 Number of Targets Neutralized — Efficient Frontier

Using the same FOMs calculated from the CAS #1 Metamodel *Total Fuel Used* and the FOMs calculated from the CAS #4 Metamodel *Targets Neutralized*, an efficient frontier plot was developed to identify the specific factor or factor interaction that would result in the best combination of MOP 1 – Fuel Consumption and MOP 4 – Number of Targets Neutralized. As before, for the CAS #1 Metamodel *Total Fuel Used* the largest negative value was considered best and assigned a value of 1. The largest positive value was considered worst and assigned a value of 0. For the CAS #4 Metamodel *Targets Neutralized*, the largest positive value was considered best and assigned a value of 1. The largest negative value was considered worst and assigned a value of 0.

Using the scaled FOM values, an efficient frontier plot was developed comparing the performance obtained in terms of total fuel used and number of targets neutralized using the top ten factors or factor interactions that generated the largest effect on total fuel used during the MEU operation. If they were not part of the top ten, scaled FOMs for the main factors that addressed DOTMLPF changes, i.e. Aircraft Type, Total Asset Qty, Assets per Launch, and Ship2Shore Dist were also plotted on the efficient frontier plot. As shown in Figure 29, the factor Ship2Shore Dist at the (average) value of 100 NM was a dominant factor. In addition, the factor interaction of Total Asset Qty at the (high) value of 115% of current doctrine interacting with Assets per Launch at the (high) value of 150% of current doctrine were also a dominant factor interaction. Also, the factor interaction of Ship2Shore Dist at the (near) value of 60 NM interacting with the factor Total asset Qty at the (low) value of 80% of current doctrine rounded out the top three in terms of dominating the remaining factors or factor interactions.

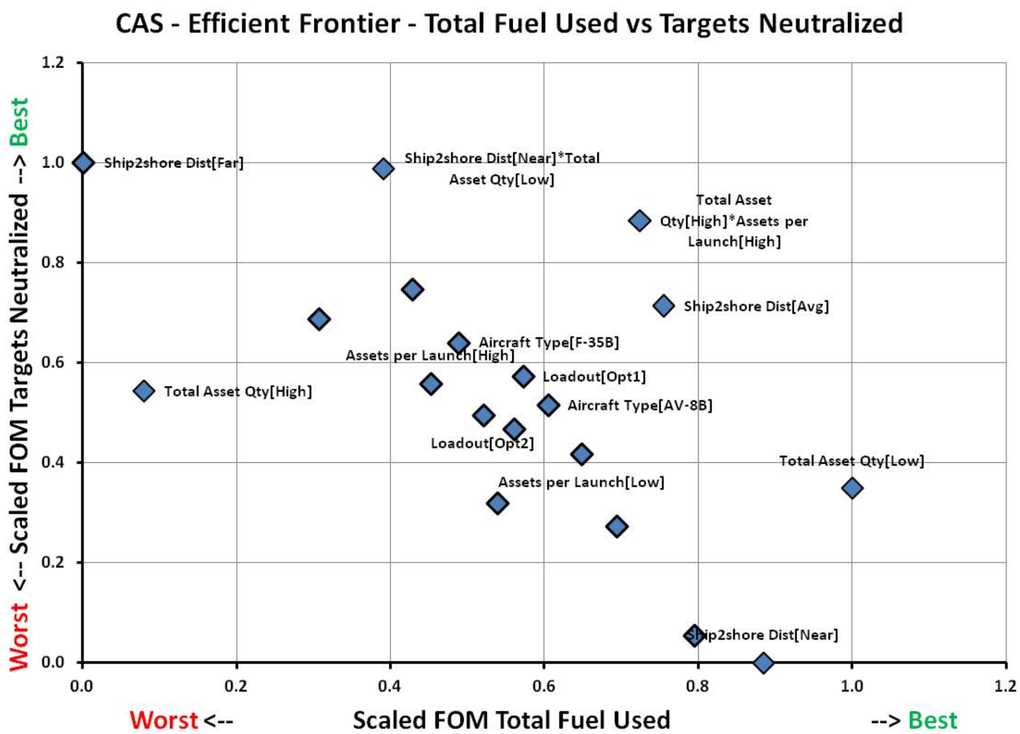

Figure 29. CAS — FOM Efficient Frontier Plot — Total Fuel Used vs. Targets Neutralized

Using these scaled FOM values, an OFOM was developed by calculating the straight line distance from each scaled FOM combination to the ideal scaled FOM value of (1,1). This distance, with the shortest distance representing the better OFOM, was plotted in Figure 30 for all of the scaled FOM combinations. For example, the interaction of the factor Total Asset Qty at the (High) value with the factor Assets per Launch at the (High) value was the closest to the ideal condition (1,1) of generating the best scaled FOM for percentage of targets neutralized and the best scaled FOM for total fuel used. The magnitude of this distance, the OFOM, was calculated to be 0.299 and was the closest of any single factor or factor interaction. The next closest distance to the ideal of (1,1) was obtained with the factor Ship2shore Dist at the (Avg) value. In this case, the calculated OFOM was 0.378.

As shown in Figure 30, the factor interaction of Total Asset Qty at the (high) value of 115% of current doctrine interacting with Assets per Launch at the (high) value of 150% of current doctrine was the closest to the ideal value of (1,1), providing the best

combination of lowest total fuel used and highest number of targets neutralized during the MEU operation. The OFOM values obtained for several of the remaining factors or factor interactions were also shown in Figure 30.

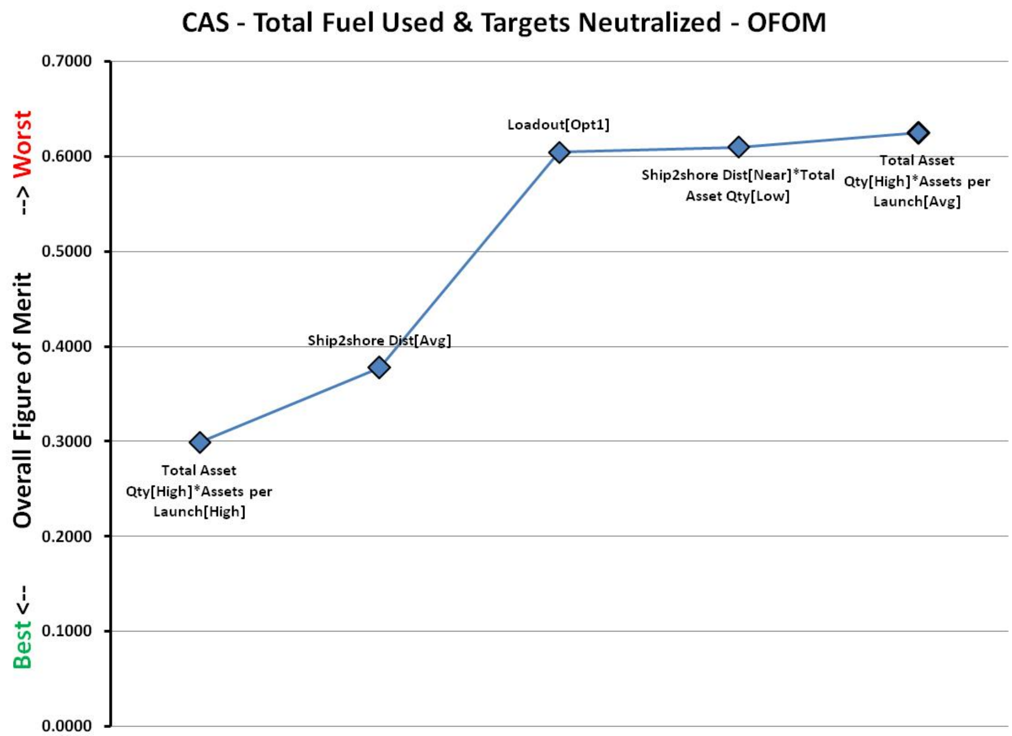

Figure 30. CAS — OFOM Ranking — Total Fuel Used vs. Targets Neutralized

8. Metamodel FOM — CAS — MOP 1 Total Fuel used vs. MOP 5 Number of Blue Force Assets Destroyed — Efficient Frontier

Using the same FOMs calculated from the CAS #1 Metamodel *Total Fuel Used* and the FOMs calculated from the CAS #6 Metamodel *Blue Casualty*, an efficient frontier plot was developed to identify the specific factor or factor interaction that would result in the best combination of MOP 1 – Fuel Consumption and MOP 5 – Number of Blue Force Assets Destroyed. As before, for the CAS #1 metamodel *Total Fuel Used* the largest negative value was considered best and assigned a value of 1. The largest positive value was considered worst and assigned a value of 0. For the CAS #6 Metamodel *Blue Casualty*, the largest negative value was considered best and assigned a value of 1. The largest positive value was considered worst and assigned a value of 0.

Using the scaled FOM values, an efficient frontier plot was developed comparing the performance obtained in terms of total fuel used and number of blue force assets destroyed using the top ten factors or factor interactions that generated the largest effect on total fuel used during the MEU operation. If they were not part of the top ten, scaled FOMs for the main factors that addressed DOTMLPF changes, i.e. Aircraft Type, Total Asset Qty, Assets per Launch, and Ship2Shore Dist were also plotted on the efficient frontier plot. As shown in Figure 31, the factor Ship2Shore Dist at the (average) value of 100 NM was a dominant factor. In addition, factor interaction of Ship2Shore Dist at the (near) value of 60 NM interacting with the factor Total asset Qty at the (high) value of 115% of current doctrine rounded was also a dominant factor interaction.

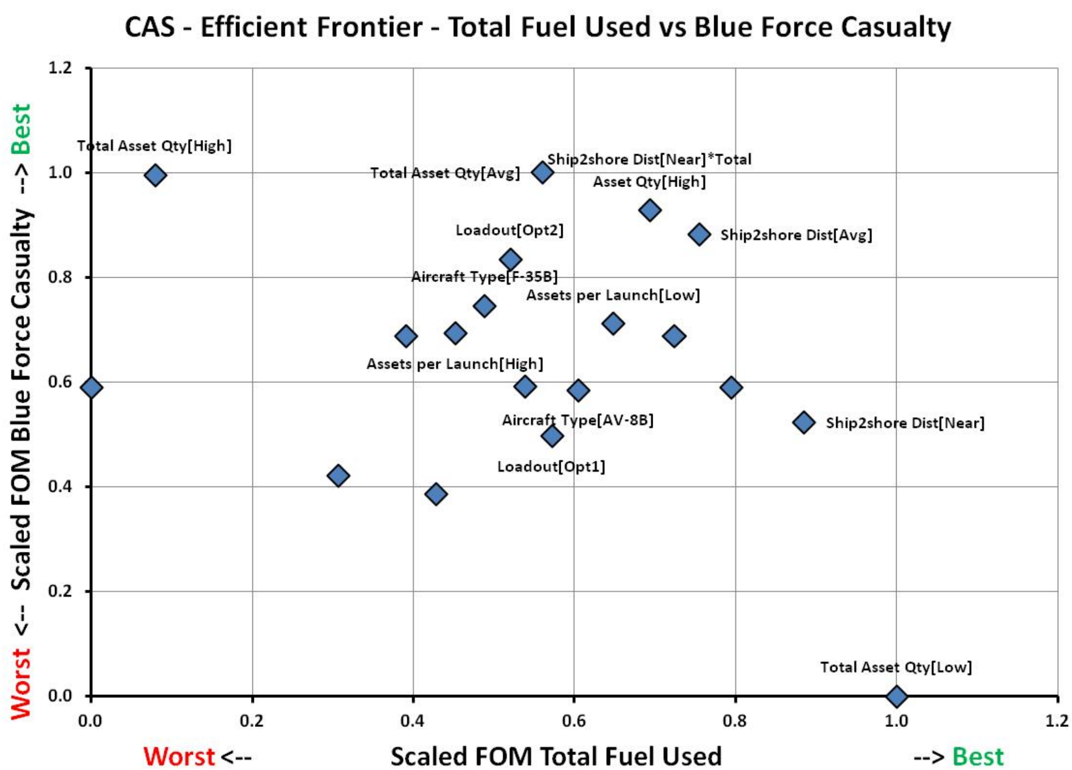

Figure 31. CAS — FOM Efficient Frontier Plot — Total Fuel Used vs. Blue Force Assets Destroyed

Using these scaled FOM values, an Overall FOM (OFOM) was developed by calculating the straight line distance from each scaled FOM combination to the ideal scaled FOM value of (1,1). This distance, with the shortest distance representing the better OFOM, was plotted in Figure 32 for all of the scaled FOM combinations. For example, the factor Ship2shore Dist at the (Avg) value was the closest to the ideal condition (1,1) of generating the best scaled FOM for percentage of blue force assets destroyed and the best scaled FOM for total fuel used. The magnitude of this distance, the OFOM, was calculated to be 0.272 and was the closest of any single factor or factor interaction.

As shown in Figure 32, the factor Ship2Shore Dist at the (average) value of 100 NM was the closest to the ideal value of (1,1), providing the best combination of lowest total fuel used and lowest number of blue force assets destroyed during the MEU operation. The OFOM values obtained for the remaining nine factors or factor interactions are also shown in Figure 32.

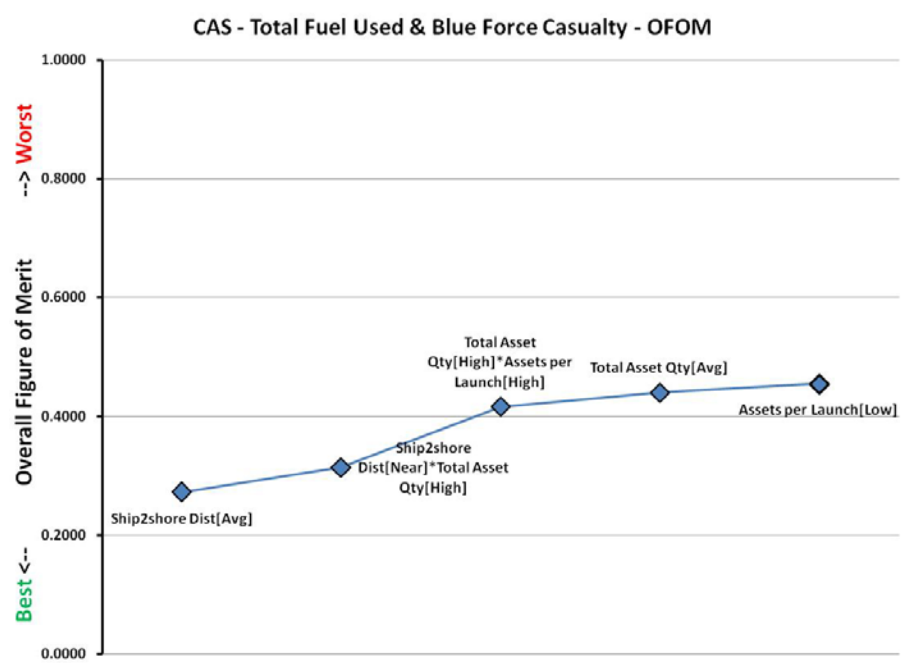

Figure 32. CAS — OFOM Ranking — Total Fuel Used vs. Blue Force Assets Destroyed

9. Metamodel FOM — CAS — MOP 1 Total Fuel used vs. Mission Success — Efficient Frontier

Using the same FOMs calculated from the CAS #1 Metamodel *Total Fuel Used* and the FOMs calculated from the CAS #9 Metamodel *Mission Success*, an efficient frontier plot was developed to identify the specific factor or factor interaction that would result in the best combination of MOP 1 – Fuel Consumption and Mission Success. As before, for the CAS #1 Metamodel *Total Fuel Used*, the FOM with the largest negative value was considered best and assigned a value of 1. The largest positive value was considered worst and assigned a value of 0. For the CAS #9 Metamodel *Mission Success*, the FOM with the largest positive value was considered best and assigned a value of 1. The largest negative value was considered worst and assigned a value of 0.

Using the scaled FOM values, an efficient frontier plot was developed comparing the performance obtained in terms of total fuel used and mission success using the top ten factors or factor interactions that generated the largest effect on total fuel used during the MEU operation. If they were not part of the top ten, scaled FOMs for the main factors that addressed DOTMLPF changes, i.e. Aircraft Type, Total Asset Qty, Assets per Launch, and Ship2Shore Dist were also plotted on the efficient frontier plot.

As shown in Figure 33, the interaction of the factor Total Asset Qty at the (high) value of 115% of current doctrine and the factor Assets per Launch at the (high) value of 150% of current doctrine was dominant factor interaction. The factor Ship2shore Dist at the (average) value of 100 NM was also a dominant factor.

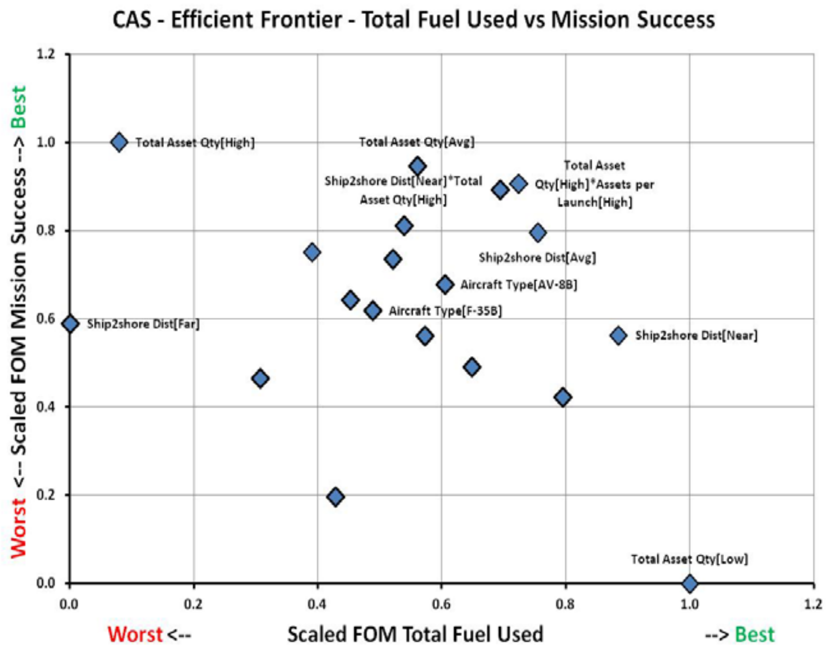

Figure 33. CAS — FOM Efficient Frontier Plot — Total Fuel Used vs. Mission Success

Using these scaled FOM values, an Overall FOM (OFOM) was developed by calculating the straight line distance from each scaled FOM combination to the ideal scaled FOM value of (1,1). This distance, with the shortest distance representing the better OFOM, was plotted in Figure 34 for all of the scaled FOM combinations. For example, the interaction of the factor Total Asset Qty at the (high) value of 115% of current doctrine and the factor Assets per Launch at the (high) value of 150% of current doctrine was the closest to the ideal condition (1,1) of generating the best scaled FOM for probability of mission success and the best scaled FOM for total fuel used. The magnitude of this distance, the OFOM, was calculated to be 0.291 and was the closest of any single factor or factor interaction.

As shown in Figure 34, the interaction of the factor Total Asset Qty at the (high) value of 115% of current doctrine and the factor Assets per Launch at the (high) value of 150% of current doctrine was the closest to the ideal value of (1,1), providing the best combination of lowest total fuel used and highest mission success of the MEU operation. The factor Ship2shore Dist at the (average) value of 100 NM was the next closest to the

ideal value of (1,1). The OFOM values obtained for the remaining factors or factor interactions are also shown in Figure 34.

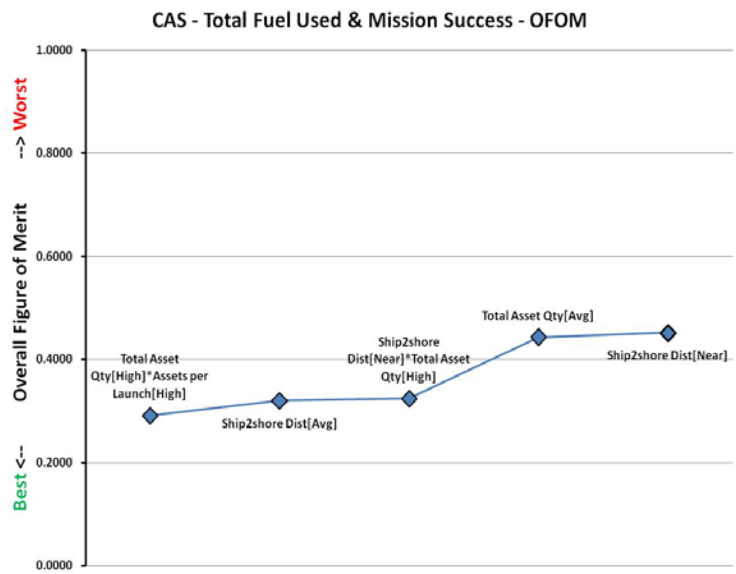

Figure 34. CAS — OFOM Ranking — Total Fuel Used vs. Mission Success

10. Metamodel Summary

The above metamodels were developed in order to quickly and accurately predict the results of an ExtendSim simulation model of an MEU operation. Specifically, each metamodel focused on predicting a specific MOP associated with the MEU operation.

Each metamodel developed was a second order polynomial that utilized nine independent variables or factors. A DOE approach was used so that the metamodel developed could also predict the potential interaction between the independent variables or factors. The primary focus of this assessment was to a) identify which factor or factor interaction had the largest impact or effect on each MOP and on mission success, b) develop a FOM to identify a dominant combination of the fuel usage (MOP 1) with the other operational aspects of a MEU (MOP 3,4,5), including mission success, and c) identify the best combination of fuel usage and operational effectiveness in terms of an OFOM, including an OFOM to assess mission success.

11. Metamodel Summary — CAS

For the CAS #1 Metamodel *Total Fuel Used*, the factor Ship2Shore Dist (ship-to-shore distance) when at the (far) distance of 300 NM, had the largest effect of increasing the total fuel used during the MEU operation. This result suggested that for a CAS operation such as the one simulated, the largest reduction in total fuel used would result from the operation occurring at the shortest distance from the shore, which in this case was 60 NM.

For the CAS #3 Metamodel *Average Mission Time*, the factor Assets per Launch when at the (high) value of 150% of current doctrine, had the largest effect of decreasing the average mission time of the MEU operation. This result suggested that for a CAS operation such as the one simulated, the largest reduction in average mission time would result from having the largest number of assets launched during the mission, which in this case was at a value of 150% of current doctrine.

Considering the combined effects of the CAS #1 Metamodel *Total Fuel Used* and the CAS #3 Metamodel *Average Mission Time*, the factor Total Asset Qty at the (low) value of 80% had the best OFOM, providing the combination of factors that most influence total fuel used and average mission time for the MEU operation. This result suggested that for a CAS operation such as the one simulated, the most effective way to reduce total fuel used and average mission time would be to reduce the total number of assets per type used during the mission, which in this case was at a value of 80% of current doctrine.

For the CAS #4 Metamodel *Targets Neutralized*, no single factor had an effect that was in the top ten, only factor interactions. The interaction between the factor Sea State at the (rough) value and the factor Assets per Launch at the (low) value of 50% of current doctrine suggested that the operational limitations imposed by a rough sea state (>8 foot waves) and a low number of (<50% current doctrine) of assets launched during the mission had the largest effect of reducing the average percentage of targets neutralized.

Considering the combined effects of the CAS #1 Metamodel *Total Fuel Used* and the CAS #4 Metamodel *Targets Neutralized*, the factor interaction of the factor Total Asset Qty at the (high) value of 115% of current doctrine interacting with the factor Assets per Launch at the (high) value of 150% of current doctrine had the best OFOM, providing the combination of factors that most influenced total fuel used and average number of target neutralized during the MEU operation. This result suggested that for a CAS operation such as the one simulated, the most effective way to reduce total fuel used and increase the number of targets neutralized would be to increase the total number of assets per type used during the mission to a value of 115% of current doctrine and increase the number of assets launched during the mission to a value of 150% of current doctrine.

For the CAS #6 Metamodel *Blue Casualty*, the factor Total Asset Qty at the (low) value of 80% of doctrine was the only single factor in the top ten that effected the percentage of blue force assets destroyed during the MEU operation. This result suggested that for a CAS operation such as the one simulated, the largest increase in the percentage of blue force assets destroyed would result from a reduction in the total number of assets per type used during the mission, which in this case would be at a value of 80% of doctrine. The alternate statement of this conclusion suggested that operations with a total number of assets per type used during the mission at a value of 115% of current doctrine would generate the lowest percentage of blue force assets destroyed.

Considering the combined effects of the CAS #1 Metamodel *Total Fuel Used* and the CAS #6 Metamodel *Blue Casualty*, the factor Ship2Shore Dist at the (average) value of 100 NM had the best OFOM, providing the combination of factors that most influence total fuel used and the number of blue force assets destroyed during the MEU operation. This result suggested that for a CAS operation such as the one simulated, the most effective way to reduce total fuel used and decrease the number of blue force assets destroyed would be to conduct the mission at an average distance, in this case 100 NM from the shore.

For the CAS #9 Metamodel *Mission Success*, the interaction of the factor Total Asset Qty at the (low) value of 80% of current doctrine and the factor Threat at the (high)

threat value had the largest effect of decreasing mission success. The interaction of the factor Total Asset Qty at the (low) value of 80% of current doctrine and the factor Threat at the (low) threat value had the largest effect of increasing mission success. This result suggested that for a CAS operation such as the one simulated, the largest increase in mission success would result from a Threat at the (low) value of threat, while using the total number of assets per type at 80% of current doctrine. Conversely, the factor Threat at the (high) threat value would have the largest effect on reducing mission success, with the same 80% of current doctrine.

Considering the combined effects of the CAS #1 Metamodel *Total Fuel Used* and the CAS #9 Metamodel *Mission Success*, the factor interaction of Total Asset Qty at the (high) value of 115% of current doctrine and Assets per Launch at the (high) value of 150% of current doctrine had the best OFOM, providing the combination of factors that most influence total fuel used and mission success of the MEU operation. This result suggested that for a CAS operation such as the one simulated, the most effective way to reduce total fuel used and increase mission success would be to conduct the mission with the total number of assets per type at 115% of current doctrine and the total number of assets per launch at 150% of current doctrine.

C. GCS RESULTS

For the GCS analysis, metamodels were developed using ten independent variables, each selected as potentially having a significant effect on either fuel efficiency or operational effectiveness. The results of the GCS analysis performed are described below.

1. Metamodel Development — Ground Combat Support (GCS)

Metamodels for the MOPs described Table 3 were next developed for a GCS operational mission of the MEU. Development of the metamodel was based on a custom DOE strategy using the ten categorical factors shown in Table 42. Also shown were the factor name for each variable and the available values for each factor. Using the JMP Pro V12 software, a custom design DOE strategy was selected which required 170

ExtendSim simulation model runs. For each of these 170 model runs, the value selected for each factor is shown in Appendix D.

Table 42. GCS DOE Factors and Range Values

Variable	Factor Name	First Value	Second Value	Third Value
Type of Artillery	Weapon Type	M777A2	Both	EFSS
Transit Medium	Transit Medium	Air	Sea	Not Used
Weather	Temperature	Cold (< 40 F)	Average (> 40 , < 80 F)	Hot (> 80 F)
Sea State	SeaState	Rough (< 1 ft waves)	Choppy (> 1 ft, < 8 ft waves)	Calm (> 8 ft waves)
Weapon Load Out	Loadout	Conventional	Precision	Not Used
Distance to Shore	Ship2Shore Dist	Far (150 NM)	Average (75 NM)	Near (10 NM)
Shore to Firing Position Distance	Shore2FirePos Dist	Far (30 Miles)	Average (15 Miles)	Near (5 Miles)
Total Weapons Quantity	Total Weapons Qty	Low (2 Howitzer / 2 EFSS)	Average (4 Howitzers / 4 EFSS)	High (6 Howitzers / 8 EFSS)
Qty of Transit Mediums per Launch	Transit Med per Launch	Low (3)	Average (6)	High (9)
Red Force Threat Level	Threat	Low	Medium	High

2. Metamodel Development — GCS Function 1.2.1

Using the DOE strategy described above, a metamodel was developed to predict the MOPs identified in Table 3 for the GCS function. The GCS #1 Metamodel *Total Fuel Used* was developed for MOP 1 and predicted the total fuel used in gallons during the MEU simulation. The GCS #6 Metamodel *Average Mission Time* was developed for

MOP 6 and predicted the average mission time in minutes for the MEU simulation. The GCS #7 Metamodel *Targets Neutralized* was developed for MOP 7 and predicted the average number of targets neutralized in percent during the MEU simulation. The GCS #8 Metamodel *Blue Casualty* was developed for MOP 8 and predicted the average number of blue force assets destroyed in percent during the MEU simulation. The GCS #10 Metamodel Mission Success was developed using the results from GCS Metamodels #6, #7, and #8 and predicted the mission success percentage of the GCS mission of the MEU operation. The specific model for each MOP is summarized in Table 43.

As with the previous CAS metamodels developed, a single intercept value and set of factor coefficients were also generated for the GCS metamodels. The same approach previously described for using the CAS metamodels was also used for using the GCS metamodels. In addition to each factor, coefficients were generated for each factor interaction. As with the CAS metamodels, only those coefficients relatively large in comparison to the intercept value were included in the GCS metamodel prediction.

Table 43. GCS Metamodels Developed

GCS Metamodel	Units	GCS MOP Predicted
GCS #1 Total Fuel Used	gallons	MOP 1: Fuel consumption
GCS #6 Average Mission Time	minutes	MOP 6: Length of mission (time)
GCS #7 Target Neutralized	percent	MOP 7: Number of targets neutralized
GCS #8 Blue Casualty	percent	MOP 8: Number of Blue Force assets destroyed
GCS #10 Mission Success	percent	Overall performance of MOP 6,7, and 8

a. GCS #1 Metamodel Total Fuel Used

Using the DOE strategy presented earlier, 136 ExtendSim simulation model runs were conducted and the total fuel used from each simulation model run recorded. Regression analysis was then conducted and a metamodel was developed to predict total

fuel used during the MEU operation. Figure 35 presents an evaluation of this metamodel and suggests that the prediction equation fits the data well. Numerically, the R^2 value of 0.998 confirms that the GCS #1 Metamodel *Total Fuel Used* was an excellent fit to the ExtendSim simulation model as shown in Table 44.

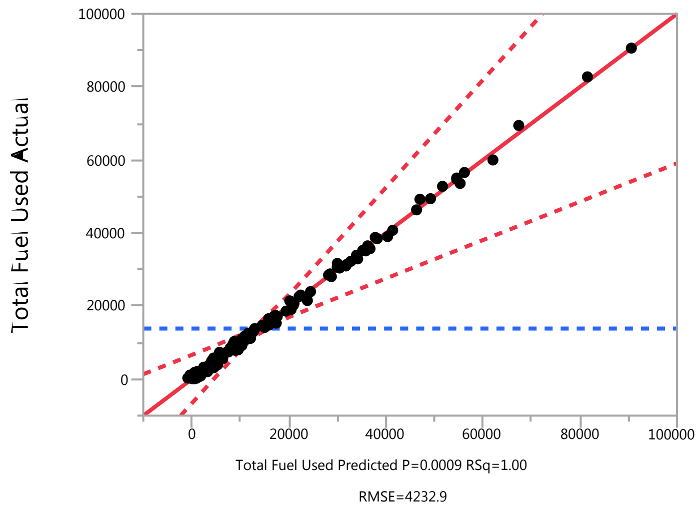

Figure 35. GCS #1 Metamodel *Total Fuel Used* (gal)

Table 44. GCS #1 Metamodel *Total Fuel Used* (gal) Regression Diagnostics

RSquare	0.99776
RSquare Adj	0.936901
Root Mean Square Error	4232.862
Mean of Response	13840.86
Observations (or Sum Wgts)	170

b. GCS #6 Metamodel Average Mission Time

Using the DOE strategy presented earlier, 136 ExtendSim simulation model runs were conducted and the average mission time from each simulation model run recorded. Regression analysis was then conducted and a metamodel was developed to predict the average mission time (as minutes) during the MEU operation. Figure 36 presents an

evaluation of this metamodel and suggests that the prediction equation fits the data well. Numerically, the R^2 value of 0.998 confirms that the GCS #6 Metamodel *Average Mission Time* was an excellent fit to the ExtendSim simulation model as shown in Table 45.

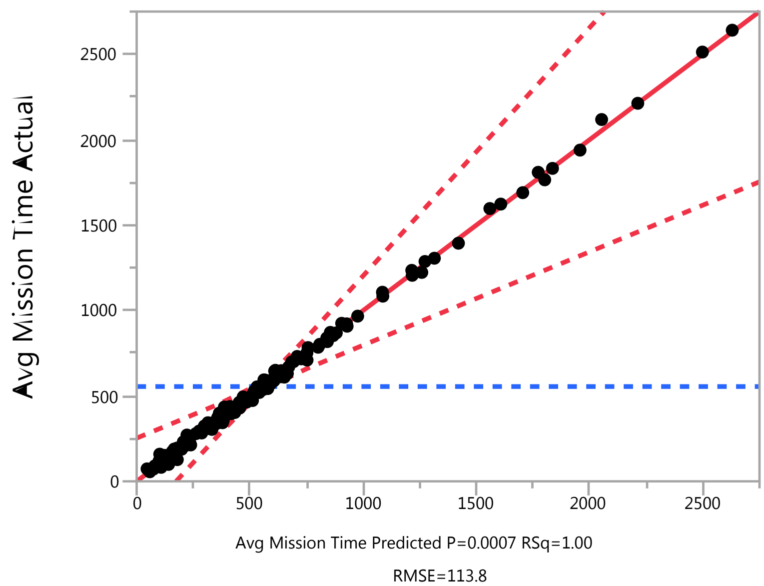

Figure 36. GCS #6 Metamodel *Average Mission Time* (minutes)

Table 45. GCS #6 Metamodel *Average Mission Time* (minutes) Regression Diagnostics

RSquare	0.997952
RSquare Adj	0.94231
Root Mean Square Error	113.8046
Mean of Response	554.9235
Observations (or Sum Wgts)	170

c. *GCS #7 Metamodel Targets Neutralized*

Using the DOE strategy presented earlier, 136 ExtendSim simulation model runs were conducted and the targets neutralized from each simulation model run recorded. Regression analysis was then conducted and a metamodel was developed to predict the

targets neutralized (as a percent of the original targets) during the MEU operation. Figure 37 presents an evaluation of this metamodel and suggests that the prediction equation fits the data well. Numerically, the R^2 value of 0.997 confirms that the GCS #7 Metamodel *Targets Neutralized* was an excellent fit to the ExtendSim simulation model as shown in Table 46.

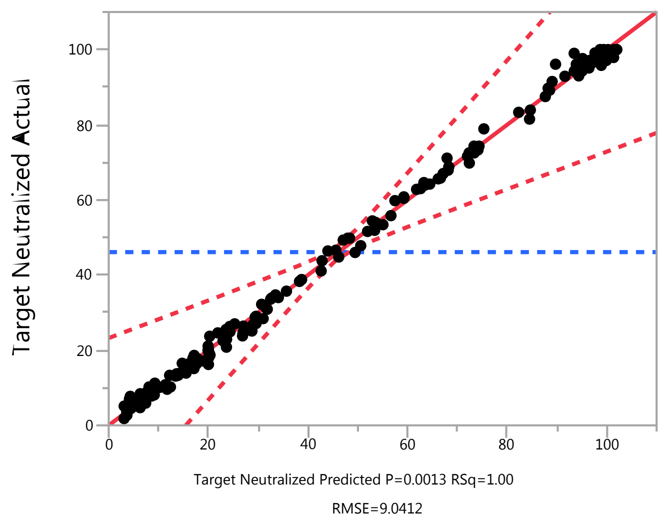

Figure 37. GCS #7 Metamodel *Targets Neutralized* (%)

Table 46. GCS #7 Metamodel *Targets Neutralized* (%) Regression Diagnostics

RSquare	0.99749
RSquare Adj	0.929313
Root Mean Square Error	9.041151
Mean of Response	46.10118
Observations (or Sum Wgts)	170

d. *GCS #8 Metamodel Blue Casualty*

Using the DOE strategy presented earlier, 136 ExtendSim simulation model runs were conducted and the blue casualties from each simulation model run recorded. Regression analysis was then conducted and a metamodel was developed to predict the

blue casualties (as a percent of the original force) during the MEU operation. Figure 38 presents an evaluation of this metamodel and suggests that the prediction equation fits the data well. Numerically, the R^2 value of 0.999 confirms that the GCS #8 Metamodel *Blue Casualty* was an excellent fit to the ExtendSim simulation model as shown in Table 47.

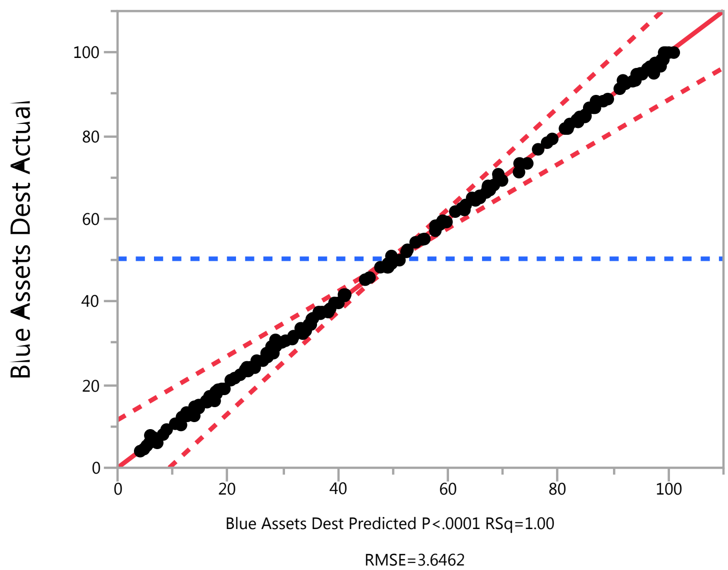

Figure 38. GCS #8 Metamodel *Blue Casualty*

Table 47. GCS #8 Metamodel *Blue Casualty* Regression Diagnostics

RSquare	0.99948
RSquare Adj	0.985356
Root Mean Square Error	3.646186
Mean of Response	50.33765
Observations (or Sum Wgts)	170

e. GCS #10 Metamodel Mission Success

Using the DOE strategy presented earlier, 136 ExtendSim simulation model runs were conducted and the mission success from each simulation model run recorded. Regression analysis was then conducted and a metamodel was developed to predict the

mission success during the MEU operation. Figure 39 presents an evaluation of this metamodel and suggests that the prediction equation fits the data well. Numerically, the R^2 value of 0.996 confirms that the GCS #10 Metamodel *Mission Success* was an excellent fit to the ExtendSim simulation model as shown in Table 48.

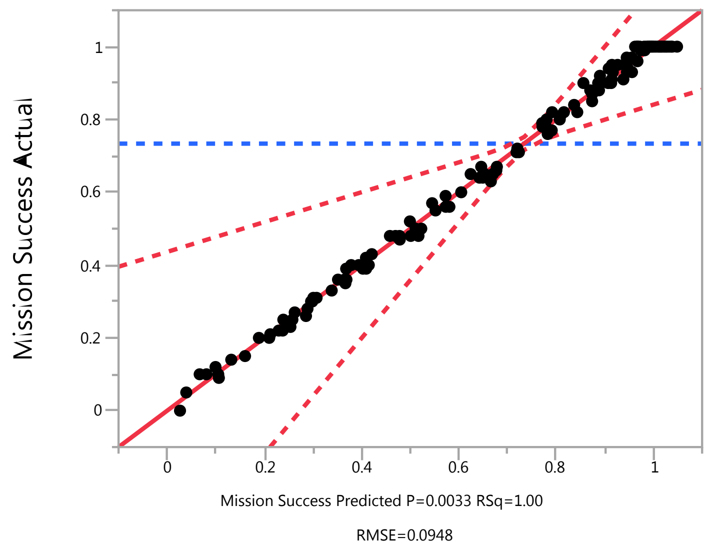

Figure 39. GCS #10 Metamodel *Mission Success*

Table 48. GCS #10 Metamodel *Mission Success* Regression Diagnostics

RSquare	0.995683
RSquare Adj	0.878412
Root Mean Square Error	16.77476
Mean of Response	35.88235
Observations (or Sum Wgts)	170

3. Metamodel Prediction — Overall Factor Effect and Desirability Analysis

Each MOP was evaluated in more detail using factor plots. These plots are particularly useful for visualizing the impact that each factor has on each MOP. Further, desirability can be defined for each MOP and preferred system configurations can be

identified based on the analysis. The best desired response, or desirability value, ranged from 0 to 1 and the value selected based on the particular MOP.

a. GCS #1 Metamodel Prediction — Overall Factor Effect and Desirability

For the GCS #1 Metamodel *Total Fuel Used*, a desirability value of 1 was assigned to the lowest predicted total fuel used per MEU operation. The curves in Figure 40 visually present the impact that each factor has on the MOP (where steeper slopes are associated with factors that have a more substantial impact on the MOP). It also shows the specific selection of factor values that maximized the desirability function (in this case, resulted in the lowest fuel consumption).

As shown, the factor Total Weapons Qty generated the largest delta in total fuel used. Total fuel used significantly decreased when going from the (low) value (2 Howitzers / 2 EFSS) to the (high) value of 6 Howitzers / 8 EFSS). Both the factor Ship2Shore Dist and the factor Transit Medium indicated there was a decrease in the total fuel used when going from the (air) value to the (sea), indicating a sea based maneuver with would generate some savings in total fuel used during the MEU operation.

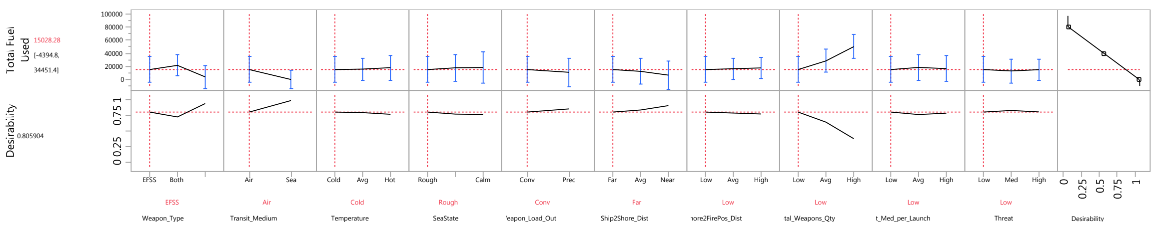

Figure 40. GCS #1 Metamodel *Total Fuel Used* Desirability

b. GCS #6 Metamodel Prediction – Overall Factor Effect and Desirability

For the GCS #6 Metamodel *Average Mission Time*, a desirability value of 1 was assigned to the lowest predicted mission time per MEU operation. This was based on the assumption that the quicker a mission was completed, the less negative impact there would be on fuel used and potential casualties. The curves in Figure 41 illustrate the sensitivity associated with each factor on the predicted metamodel response. It also

shows the specific selection of factor values that maximized the desirability of the lowest possible average mission time for the MEU operation.

As shown, the effect of the factor Total Weapons Qty generated the largest delta in average mission time. The average mission time significantly increased when going from the (low) value of (2 Howitzers / 2 EFSS) to the (high) value of (6 Howitzers / 8 EFSS). The factor Ship2Shore Dist also reduced average mission time when going from a (far) value of 150 NM to a (near) value of 10 NM.

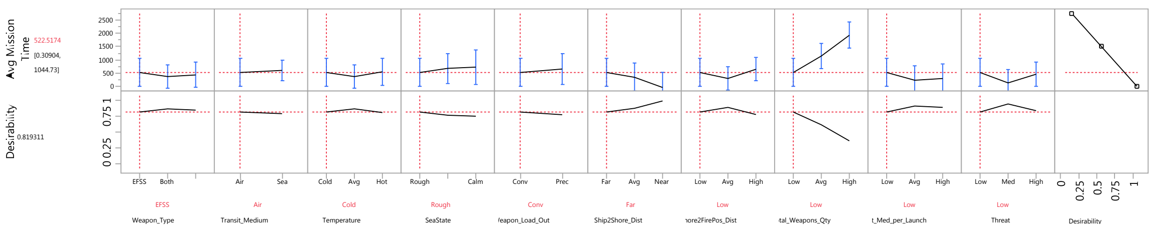

Figure 41. GCS #6 Metamodel *Average Mission Time* Desirability

c. *GCS #7 Metamodel Prediction – Overall Factor Effect and Desirability*

For the GCS #7 Metamodel *Targets Neutralized*, a desirability value of 1 was assigned to the highest predicted percentage of targets neutralized during the MEU operation. The curves in Figure 42 illustrate the sensitivity associated with each factor on the predicted metamodel response. It also shows the specific selection of factor values that maximized the desirability of the highest percentage of targets neutralized during the MEU operation. As shown, the factor Weapon Type, Total Weapons Qty, and Threat had a significant effect on the percentage of targets neutralized during the MEU operation. Of particular note was the optimum effect of factor Weapon Type at the value of (both).

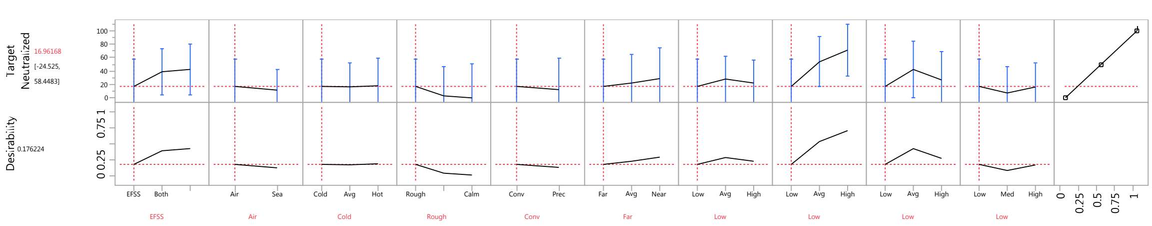

Figure 42. GCS #7 Metamodel *Targets Neutralized* Desirability

d. GCS #8 Metamodel Prediction — Overall Factor Effect and Desirability

For the GCS #8 Metamodel *Blue Casualty*, a desirability value of 1 was assigned to the lowest percentage of blue force assets destroyed during the MEU operation. The curves in Figure 43 illustrate the sensitivity associated with each factor on the predicted metamodel response. It also shows the specific selection of factor values that maximized the desirability of the lowest percentage of blue force assets destroyed during the MEU operation. As shown, several factors had an effect on minimizing the percentage of blue force assets destroyed during the MEU operation. Of particular note was the effect of the factor Threat, where going from the (low) threat value associated with a more benign threat to the (high) threat value associated with a more sophisticated threat resulted in a significant increase in the percentage of blue force assets destroyed. Also, the effect of the factor Total Weapons Qty had a significant effect in reducing the percentage of blue force assets destroyed when going from the (low) value of (2 Howitzers / 2 EFSS) to the (high) value of (6 Howitzers / 8 EFSS).

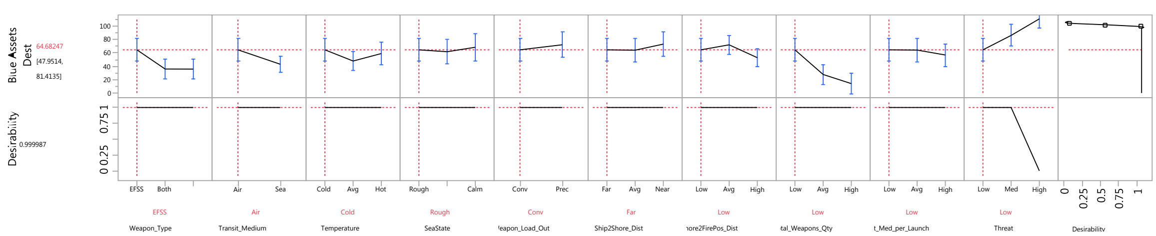

Figure 43. GCS #8 Metamodel *Blue Casualty* Desirability

e. GCS #10 Metamodel Prediction — Overall Factor Effect and Desirability

For the GCS #10 metamodel *Mission Success*, a desirability value of 1 was assigned to the highest predicted mission success of the MEU operation. The curves in Figure 44 illustrate the sensitivity associated with each factor on the predicted metamodel response. It also shows the specific selection of factor values that maximized the desirability of the highest mission success of the MEU operation.

As shown, several of the nine factors had a significant effect on maximizing mission success of the MEU operation. Of particular note was the positive effect of the

factor Weapon Type at the (Both) value of using both the EFSS and the M777A2, Ship2Shore Dist at a (near) value of 10 NM, and a Total Weapons Quantity at an (average) value of (4 Howitzers / 4 EFSS).

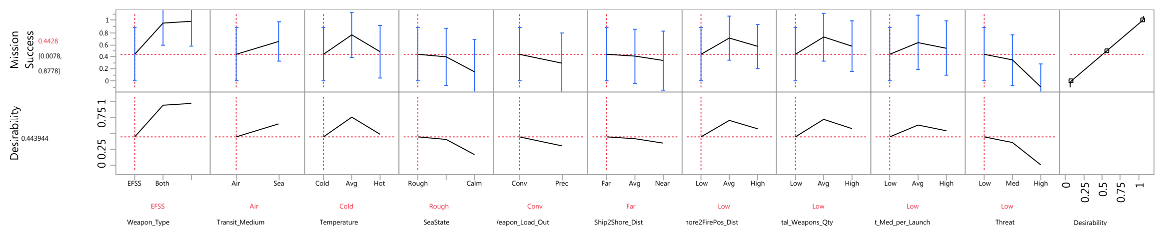

Figure 44. GCS #10 Metamodel *Mission Success* Desirability

4. Metamodel Factor Analysis

For each metamodel developed, an analysis was conducted in order to a) identify which metamodel factor or factor interactions had the largest impact on each MOP, b) identify the most significant interactions between MOPs, and c) identify the best combination of fuel usage and operational effectiveness in terms of the MOPs identified. The results of this analysis, contained in Appendix E, was used to prioritize the hundred plus factors initially produced by the DOE linear regression, down to a manageable level for consideration with the following efficient frontier analysis.

5. Metamodel Figure of Merit — Efficient Frontier Analysis

A FOM was calculated for each of the top ten factors or factor interactions that had the largest impact on the response predicted from each of the four metamodels developed. If they were not part of the top ten, FOMs were also calculated for the main factors that addressed DOTMLPF changes, i.e. Weapon Type, Transit Medium, Weapon Loadout, Total Weapon Qty, Shore2Fire Pos, Ship2Shore Dist, and Transit Medium per Launch. Using the FOMs calculated from the GCS#1 metamodel *Total Fuel Used*, an efficient frontier plot was generated comparing these FOMs to those generated for the same factors or factor interactions from the other three GCS metamodels.

a. GCS #1 Metamodel Total Fuel Used FOM

For the GCS #1 Metamodel *Total Fuel Used*, a FOM was calculated for each of the top ten factors or factor interactions that had the largest impact on the total fuel used during the MEU operation. This FOM was obtained by dividing the factor value or factor interaction value by the interceptor. The FOM for each of the top ten factors or factor interactions are shown in Table 49. Also shown in the table were those FOMs, if not part of the top ten, for the main factors that addressed DOTMLPF changes.

Table 49. GCS #1 Metamodel *Total Fuel Used* — FOM

Factor or Factor Interaction Used	GCS #1 FOM
Transit_Medium[Air]	0.699
Transit_Medium[Sea]	-0.699
Total_Weapons_Qty[High]	0.558
Ship2Shore_Dist[Far]	0.542
Ship2Shore_Dist[Near]	-0.509
Total_Weapons_Qty[Low]	-0.494
Weapon_Type[Both]	0.476
Weapon_Type[M777A2]*Transit_Medium[Air]	-0.366
Weapon_Type[M777A2]*Transit_Medium[Sea]	0.366
Transit_Medium[Air]*Total_Weapons_Qty[High]	0.362
Weapon_Type[M777A2]	-0.291
Weapon_Type[EFSS]	-0.220
Transit_Med_per_Launch[Low]	-0.124
Shore2FirePos_Dist[High]	0.086
Transit_Med_per_Launch[High]	-0.068
Total_Weapons_Qty[Avg]	0.067
Shore2FirePos_Dist[Low]	0.060
Shore2FirePos_Dist[Avg]	0.040
Transit_Med_per_Launch[Avg]	0.039
Ship2Shore_Dist[Avg]	-0.033
Weapon_Load_Out[Conv]	-0.032

b. GCS #6 Metamodel Average Mission Time FOM

For the GCS #6 Metamodel *Average Mission Time*, a FOM was calculated for the exact same ten factors or factor interactions that had the largest impact on the total fuel used during the MEU operation. This FOM was obtained by dividing the factor value or factor interaction value by interceptor. The FOM for each of the top ten factors or factor interactions are shown in Table 50. Also shown were those FOMs, if not part of the top ten, for the main factors that addressed DOTMLPF changes.

Table 50. GCS #6 Metamodel *Average Mission Time* — FOM

Factor or Factor Interaction Used	GCS #6 FOM
Transit_Medium[Air]	-0.179
Transit_Medium[Sea]	0.179
Total_Weapons_Qty[High]	0.474
Ship2Shore_Dist[Far]	0.655
Ship2Shore_Dist[Near]	-0.518
Total_Weapons_Qty[Low]	-0.370
Weapon_Type[Both]	0.081
Weapon_Type[M777A2]*Transit_Medium[Air]	-0.121
Weapon_Type[M777A2]*Transit_Medium[Sea]	0.121
Transit_Medium[Air]*Total_Weapons_Qty[High]	0.016
Weapon_Type[M777A2]	0.098
Weapon_Type[EFSS]	-0.012
Transit_Med_per_Launch[Low]	-0.045
Shore2FirePos_Dist[High]	0.032
Transit_Med_per_Launch[High]	-0.248
Total_Weapons_Qty[Avg]	-0.013
Shore2FirePos_Dist[Low]	0.096
Shore2FirePos_Dist[Avg]	-0.113
Transit_Med_per_Launch[Avg]	0.047
Ship2Shore_Dist[Avg]	-0.137
Weapon_Load_Out[Conv]	-0.002

c. GCS #7 Metamodel Targets Neutralized FOM

For the GCS #7 Metamodel *Targets Neutralized*, a FOM was calculated for the exact same ten factors or factor interactions that had the largest impact on the total fuel used during the MEU operation. This FOM was obtained by dividing the factor value or

factor interaction value by the interceptor. The FOM for each of the top ten factors or factor interactions are shown in Table 51. Also shown were those FOMs, if not part of the top ten, for the main factors that addressed DOTMLPF changes.

Table 51. GCS #7 Metamodel *Targets Neutralized* — FOM

Factor or Factor Interaction Used	GCS #7 FOM
Transit_Medium[Air]	-0.0219
Transit_Medium[Sea]	0.0219
Total_Weapons_Qty[High]	0.4946
Ship2Shore_Dist[Far]	0.0306
Ship2Shore_Dist[Near]	-0.0146
Total_Weapons_Qty[Low]	-0.5383
Weapon_Type[Both]	0.2994
Weapon_Type[M777A2]*Transit_Medium[Air]	-0.1403
Weapon_Type[M777A2]*Transit_Medium[Sea]	0.1403
Transit_Medium[Air]*Total_Weapons_Qty[High]	-0.0022
Weapon_Type[M777A2]	-0.0154
Weapon_Type[EFSS]	0.0534
Transit_Med_per_Launch[Low]	-0.0713
Shore2FirePos_Dist[High]	-0.0508
Transit_Med_per_Launch[High]	0.0210
Total_Weapons_Qty[Avg]	-0.0058
Shore2FirePos_Dist[Low]	-0.0274
Shore2FirePos_Dist[Avg]	0.0286
Transit_Med_per_Launch[Avg]	-0.0880
Ship2Shore_Dist[Avg]	-0.0160
Weapon_Load_Out[Conv]	0.0255

d. GCS #8 Metamodel Blue Casualty FOM

For the GCS #8 Metamodel *Blue Casualty*, a FOM was calculated for the exact same ten factors or factor interactions that had the largest impact on the total fuel used during the MEU operation. This FOM was obtained by dividing the factor value or factor interaction value by the interceptor. The FOM for each of the top ten factors or factor interactions are shown in Table 52. Also shown were those FOMs, if not part of the top ten, for the main factors that addressed DOTMLPF changes.

Table 52. GCS #8 Metamodel *Blue Casualty* — FOM

Factor or Factor Interaction Used	GCS #8 FOM
Transit_Medium[Air]	-0.1815
Transit_Medium[Sea]	0.1815
Total_Weapons_Qty[High]	-0.3633
Ship2Shore_Dist[Far]	0.0127
Ship2Shore_Dist[Near]	0.0220
Total_Weapons_Qty[Low]	0.4092
Weapon_Type[Both]	-0.0630
Weapon_Type[M777A2]*Transit_Medium[Air]	-0.2310
Weapon_Type[M777A2]*Transit_Medium[Sea]	0.2310
Transit_Medium[Air]*Total_Weapons_Qty[High]	0.0013
Weapon_Type[M777A2]	0.1406
Weapon_Type[EFSS]	-0.0244
Transit_Med_per_Launch[Low]	-0.0786
Shore2FirePos_Dist[High]	-0.0174
Transit_Med_per_Launch[High]	-0.0585
Total_Weapons_Qty[Avg]	0.0152
Shore2FirePos_Dist[Low]	-0.0479
Shore2FirePos_Dist[Avg]	0.0155
Transit_Med_per_Launch[Avg]	-0.0148
Ship2Shore_Dist[Avg]	-0.0347
Weapon_Load_Out[Conv]	0.2390

e. GCS #10 Metamodel Mission Success FOM

For the GCS #10 Metamodel *Mission Success*, a FOM was calculated for the exact same ten factors or factor interactions that had the largest impact on the total fuel used during the MEU operation. This FOM was obtained by dividing the factor value or factor interaction value by interceptor. The FOM for each of the top ten factors or factor interactions are shown in Table 53. Also shown were those FOMs, if not part of the top ten, for the main factors that addressed DOTMLPF changes.

Table 53. GCS #10 Metamodel *Mission Success* — FOM

Factor or Factor Interaction Used	GCS #10 FOM
Transit_Medium[Air]	0.0930
Transit_Medium[Sea]	-0.0930
Total_Weapons_Qty[High]	0.1284
Ship2Shore_Dist[Far]	-0.0947
Ship2Shore_Dist[Near]	0.0366
Total_Weapons_Qty[Low]	-0.2673
Weapon_Type[Both]	0.0482
Weapon_Type[M777A2]*Transit_Medium[Air]	0.1511
Weapon_Type[M777A2]*Transit_Medium[Sea]	-0.1511
Transit_Medium[Air]*Total_Weapons_Qty[High]	-0.0123
Weapon_Type[M777A2]	-0.0770
Weapon_Type[EFSS]	-0.0071
Transit_Med_per_Launch[Low]	0.0396
Shore2FirePos_Dist[High]	-0.0167
Transit_Med_per_Launch[High]	0.0819
Total_Weapons_Qty[Avg]	-0.0290
Shore2FirePos_Dist[Low]	0.0656
Shore2FirePos_Dist[Avg]	-0.0142
Transit_Med_per_Launch[Avg]	0.0068
Ship2Shore_Dist[Avg]	0.0581
Weapon_Load_Out[Conv]	-0.0141

6. Metamodel FOM — GCS — MOP 1 Total Fuel Used vs. MOP 6 Length of Mission — Efficient Frontier

Using the FOMs calculated from the GCS #1 Metamodel *Total Fuel Used* and from the GCS #6 Metamodel *Average Mission Time*, an efficient frontier plot was developed to identify the specific factor or factor interaction that would result in the best combination of MOP 1 — Fuel Consumption and MOP 6 — Length of Mission. Prior to developing the efficient frontier plot, each FOM was linearly scaled from 0 to 1, using the minimum and maximum values obtained from the ten FOMs calculated. For the GCS #1 Metamodel *Total Fuel Used*, the largest negative value was considered best and assigned a value of 1. The largest positive value was considered worst and assigned a value of 0. For the GCS #6 Metamodel *Average Mission Time*, the largest negative value was considered best and assigned a value of 1. The largest positive value was considered worst and assigned a value of 0.

Using the scaled FOM values, an efficient frontier plot was developed comparing the performance obtained in terms of total fuel used and average mission time using the top ten factors or factor interactions that generated the largest effect on total fuel used during the MEU operation. If they were not part of the top ten, scaled FOMs for the main factors that addressed DOTMLPF changes, i.e. Weapon Type, Transit Medium, Weapon Loadout, Total Weapon Qty, Shore2Fire Pos, Ship2Shore Dist, and Transit Medium per Launch were also plotted on the efficient frontier plot.

As shown in Figure 45, the factor Total Weapons Qty at the (low) value of (2 Howitzers / 2 EFSS) and the factor Ship2Shore Dist at the (near) value of 10 NM dominated all of the remaining factors or factor interactions.

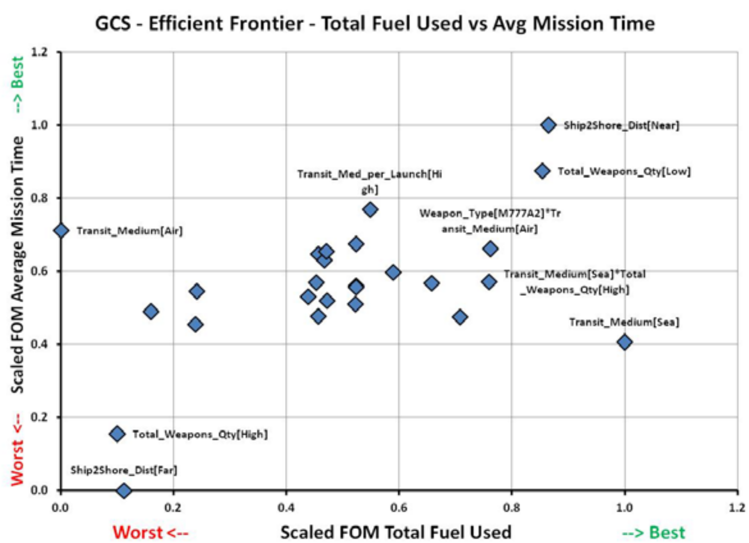

Figure 45. GCS — FOM Efficient Frontier Plot — Total Fuel Used vs. Average Mission Time

Using these scaled FOM values, an OFOM was developed by calculating the straight line distance from each scaled FOM combination to the ideal scaled FOM value of (1,1). This distance, with the shortest distance representing the better OFOM, was plotted in Figure 46 for all of the scaled FOM combinations.

As shown in Figure 46, the factor Ship2Shore Dist at the (near) value of 10 NM was the closest to the ideal value of (1,1), providing the best combination of lowest total

fuel used and shortest average mission time for the MEU operation. The OFOM values obtained for several of the remaining factors or factor interactions are also shown in Figure 46.

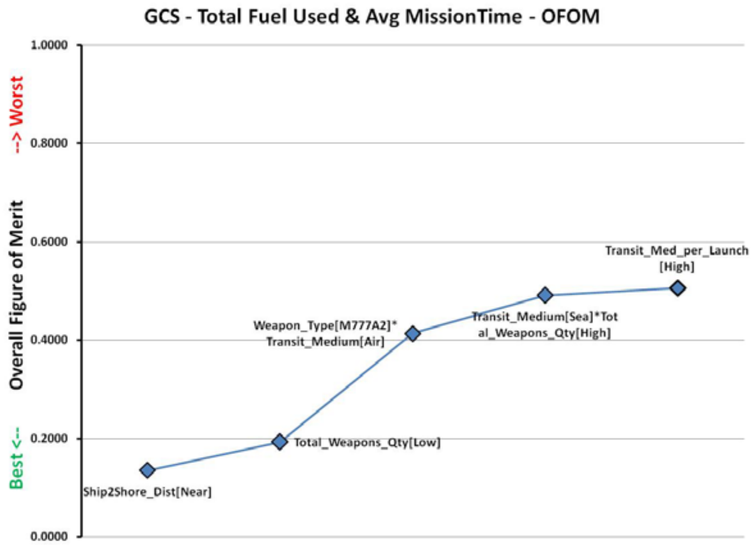

Figure 46. GCS — OFOM Ranking — Total Fuel Used vs. Average Mission Time

7. Metamodel FOM — GCS — MOP 1 Total Fuel Used vs. MOP 7 Number of Targets Neutralized — Efficient Frontier

Using the same FOMs calculated from the GCS #1 Metamodel *Total Fuel Used* and the FOMs calculated from the GCS #7 Metamodel *Targets Neutralized*, an efficient frontier plot was developed to identify the specific factor or factor interaction that would result in the best combination of MOP 1 — Fuel Consumption and MOP 7 — Number of Targets Neutralized. For the GCS #1 metamodel *Total Fuel Used*, the largest negative value was considered best and assigned a value of 1. The largest positive value was considered worst and assigned a value of 0. For the GCS #7 Metamodel *Targets Neutralized*, the largest positive value was considered best and assigned a value of 1. The largest negative value was considered worst and assigned a value of 0.

Using the scaled FOM values, an efficient frontier plot was developed comparing the performance obtained in terms of total fuel used and number of targets neutralized

using the ten factors or factor interactions that generated the largest effect on total fuel used during the MEU operation. If they were not part of the top ten, scaled FOMs for the main factors that addressed DOTMLPF changes, i.e. Weapon Type, Transit Medium, Weapon Loadout, Total Weapon Qty, Shore2FirePos Dist, Ship2Shore Dist, and Transit Medium per Launch were also plotted on the efficient frontier plot.

As shown in Figure 47, the factor Transit Medium at the (sea) value was a dominant factor. In addition, the factor Weapon Type at the (M777A2) value and the Ship2Shore Dist at the (near) value of 10 NM were also near the frontier.

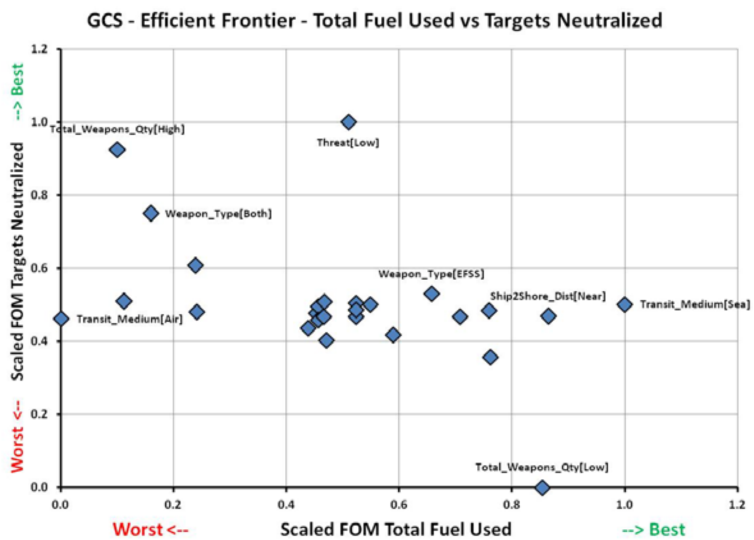

Figure 47. GCS — FOM Efficient Frontier Plot — Total Fuel Used vs. Targets Neutralized

Using these scaled FOM values, an OFOM was developed by calculating the straight line distance from each scaled FOM combination to the ideal scaled FOM value of (1,1). This distance, with the shortest distance representing the better OFOM, was plotted in Figure 48 for all of the scaled FOM combinations.

As shown in Figure 48, the factor Threat at the (low) threat value was the closest to the ideal value of (1,1), providing the best combination of lowest total fuel used and highest number of targets neutralized during the MEU operation. The OFOM values

obtained for several of the remaining factors or factor interactions are also shown in Figure 48.

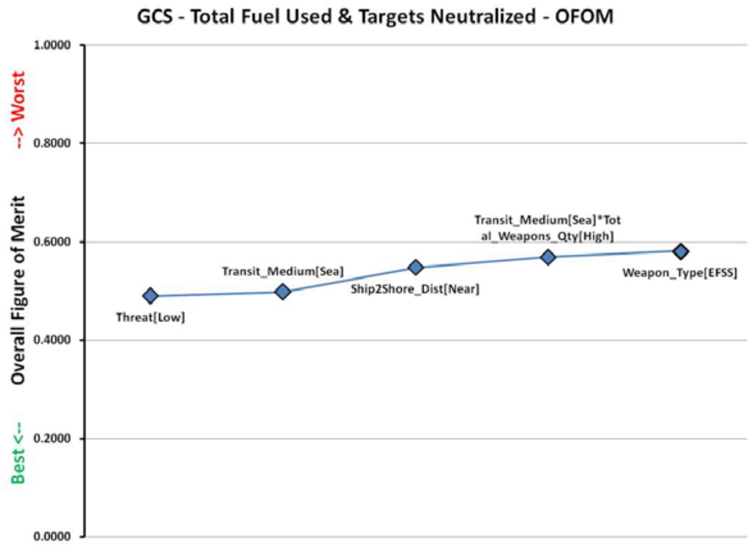

Figure 48. GCS — OFOM Ranking — Total Fuel Used vs. Targets Neutralized

8. Metamodel FOM — GCS — MOP 1 Total Fuel Used vs. MOP 8 Number of Blue Force Assets Destroyed — Efficient Frontier

Using the same FOMs calculated from the GCS #1 Metamodel *Total Fuel Used* and the FOMs calculated from the GCS #8 Metamodel *Blue Casualty*, an efficient frontier plot was developed to identify the specific factor or factor interaction that would result in the best combination of MOP 1 — Fuel Consumption and MOP 8 — Number of blue force Assets Destroyed. For the GCS #1 Metamodel *Total Fuel Used*, the largest positive value was considered worst and assigned a value of 0. For the GCS #8 metamodel *Blue Casualty*, the largest negative value was considered best and assigned a value of 1. The largest positive value was considered worst and assigned a value of 0.

Using the scaled FOM values, an efficient frontier plot was developed comparing the performance obtained in terms of total fuel used and number of blue force assets destroyed using the ten factors or factor interactions that generated the largest effect on total fuel used during the MEU operation. If they were not part of the top ten, scaled FOMs for the main factors that addressed DOTMLPF changes, i.e. Weapon Type, Transit

Medium, Weapon Loadout, Total Weapon Qty, Shore2Fire Pos, Ship2Shore Dist, and Transit Medium per Launch were also plotted on the efficient frontier plot.

As shown in Figure 49, the interaction of the factor Weapon Type at the (M777A2) value and the factor Transit Medium at the (air) value were a dominant combination. In terms of a single factor, the factors Weapon Type at the (EFSS) value and the factor Ship2Shore Dist at the (near) value of 10 NM were also near the frontier.

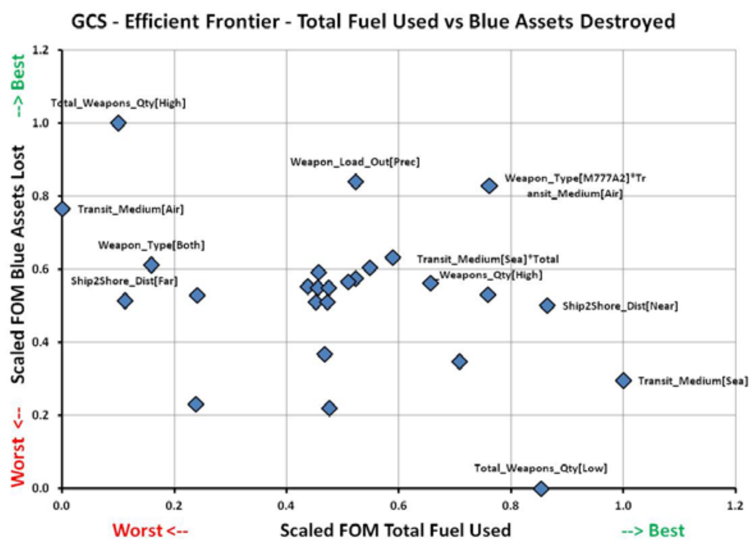

Figure 49. GCS — FOM Efficient Frontier Plot — Total Fuel Used vs. Blue Force Assets Destroyed

Using these scaled FOM values, an OFOM was developed by calculating the straight line distance from each scaled FOM combination to the ideal scaled FOM value of (1,1). This distance, with the shortest distance representing the better OFOM, was plotted in Figure 50 for all of the scaled FOM combinations.

As shown in Figure 50, the interaction of the factor Weapon Type at the (M777A2) value and the factor Transit Medium at the (air) value was the closest to the ideal value of (1,1), providing the best combination of lowest total fuel used and lowest number of blue force assets destroyed during the MEU operation. The OFOM values obtained for several of the remaining factors or factor interactions are also shown in Figure 50.

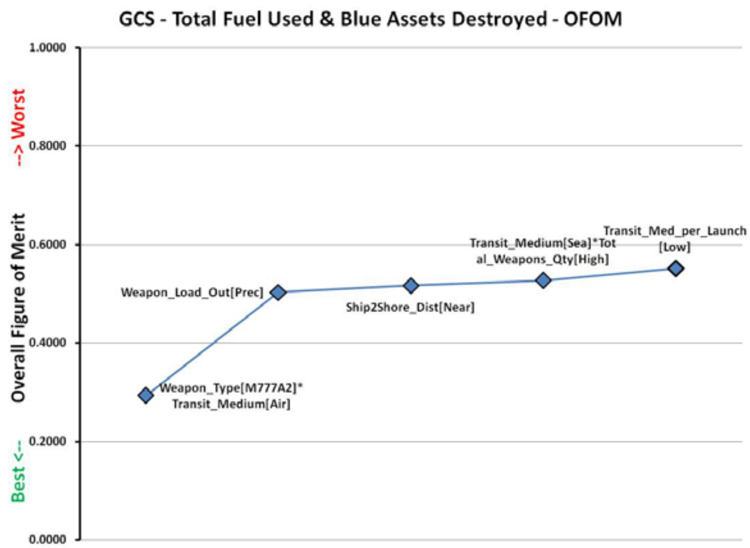

Figure 50. GCS — OFOM Ranking — Total Fuel Used vs. Blue Force Assets Destroyed

9. Metamodel FOM — GCS — MOP 1 Total Fuel Used vs. Mission Success — Efficient Frontier

Using the same FOMs calculated from the GCS #1 Metamodel *Total Fuel Used* and the FOMs calculated from the GCS #10 Metamodel *Mission Success*, an efficient frontier plot was developed to identify the specific factor or factor interaction that would result in the best combination of MOP 1 — Fuel Consumption and Mission Success. As before, for the GCS #1 Metamodel *Total Fuel Used*, the FOM with the largest negative value was considered best and assigned a value of 1. The largest positive value was considered worst and assigned a value of 0. For the GCS #10 Metamodel *Mission Success*, the FOM with the largest positive value was considered best and assigned a value of 1. The largest negative value was considered worst and assigned a value of 0.

Using the scaled FOM values, an efficient frontier plot was developed comparing the performance obtained in terms of total fuel used and mission success using the top ten factors or factor interactions that generated the largest effect on total fuel used during the MEU operation. If they were not part of the top ten, scaled FOMs for the main factors that addressed DOTMLPF changes, i.e. Aircraft Type, Total Asset Qty, Assets per Launch, and Ship2Shore Dist were also plotted on the efficient frontier plot.

As shown in Figure 51, the factor Ship2Shore Dist at the (near) value of 10 NM was a dominant factor. In addition, the interaction of the factor Transit Medium at the (Sea) value and the factor Weapon Qty at the (high) value of (6 Howitzers / 8 EFSS) also dominated several other factors. The factor Weapon Type at the (EFSS) value was also a dominant factor.

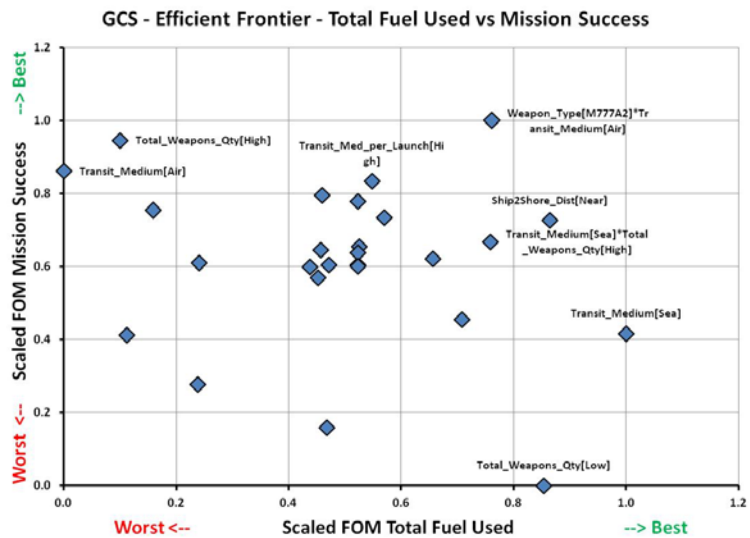

Figure 51. GCS — FOM Efficient Frontier Plot — Total Fuel Used vs. Mission Success

Using these scaled FOM values, an Overall FOM (OFOM) was developed by calculating the straight line distance from each scaled FOM combination to the ideal scaled FOM value of (1,1). The top five OFOMs, i.e., those with shortest distance, were plotted in Figure 52.

As shown in Figure 52, the factor Ship2Shore Dist at the (near) value of 10 NM was the closest to the ideal value of (1,1), providing the best combination of lowest total fuel used and highest mission success of the MEU operation. The factor Weapon Type at the (EFSS) value had the second best OFOM. The remaining three best OFOM values were also shown in Figure 52.

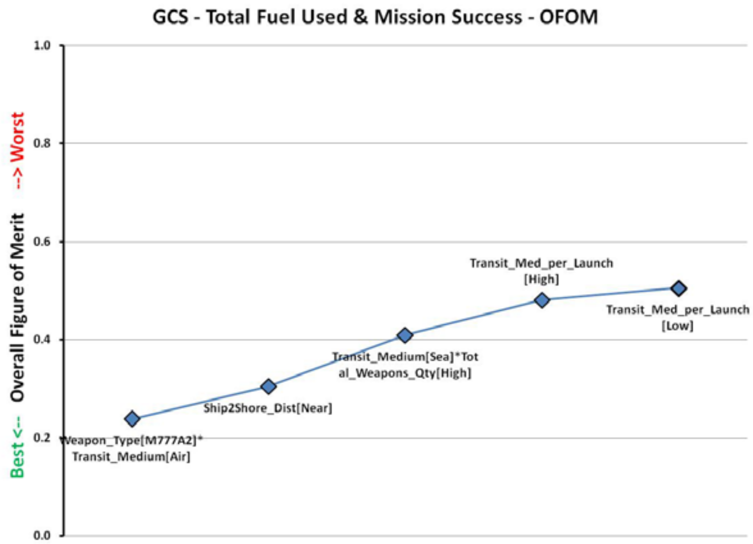

Figure 52. GCS — OFOM Ranking — Total Fuel Used vs. Mission Success

10. Metamodel Summary — GCS MOP Summary

The above metamodels were developed in order to quickly and accurately predict the results of an ExtendSim simulation model of an MEU operation. Specifically, each metamodel focused on predicting a specific MOP associated with the MEU operation.

Each metamodel developed was a second order polynomial that utilized ten independent variables or factors. A DOE approach was used so that the metamodel developed could also predict the potential interaction between the independent variables or factors. The primary focus of this assessment was to a) identify which factor or factor interaction had the largest impact or effect on each MOP, b) develop a FOM to identify a dominant combination of the fuel usage (MOP 1) with the other operational aspects of an MEU (MOP 6,7,8), and c) identify the best combination of fuel usage and operational effectiveness in terms of an OFOM, including an OFOM to assess mission success.

11. Metamodel Summary — GCS

For the GCS #1 Metamodel *Total Fuel Used*, the factor Transit Medium at the (air) value, had the largest effect of increasing the total fuel used during the MEU operation. The factor Transit Medium at the (sea) value, had the largest effect of decreasing the total fuel used during the MEU operation. This result suggested that for a

GCS operation such as the one simulated, less fuel would be used during a mission that utilized sea based transit of the combat assets to the shore position rather than air based transit.

For the GCS #6 Metamodel *Average Mission Time*, the factor Ship2Shore Dist when at the (far) value of 150 NM, had the largest effect of increasing the average mission time of the MEU operation. Conversely, the factor Ship2Shore Dist when at the (near) value of 10 NM, had the largest effect of decreasing the average mission time of the MEU operation. This result suggested that for a GCS operation such as the one simulated, the largest reduction in average mission time would result from a short distance to the shore and in this case a distance of 10 NM.

Considering the combined effects of the GCS #1 Metamodel *Total Fuel Used* and the GCS #6 Metamodel *Average Mission Time*, the factor Ship2Shore Dist at the (low) value of 10 NM had the best OFOM, providing the combination of factors that most influence total fuel used and average mission time for the MEU operation. This result suggested that for a GCS operation such as the one simulated, the most effective way to reduce total fuel used and average mission time would be to reduce the distance from shore to a value of 10 NM.

For the GCS #7 Metamodel *Targets Neutralized*, the factor Threat at the (low) threat value had the largest effect of increasing the percentage of targets neutralized during the MEU operation. The interaction between the factor Total Weapons Qty at the (low) value of (2 Howitzers / 2 EFSS) and the factor Threat at the (low) threat value had the largest effect of decreasing the percentage of targets neutralized.

Considering the combined effects of the GCS #1 Metamodel *Total Fuel Used* and the GCS #7 Metamodel *Targets Neutralized*, the factor Threat at the (low) threat value had the best OFOM, providing the combination of factors that most influence total fuel used and average number of targets neutralized during the MEU operation. The factors Transit Medium at the (sea) value and the factor Ship2Shore Dist at the (near) value of 10 NM were almost equal to the factor Threat at the (low) threat value. The interaction of the factor Transit Medium at the (sea) value and the factor Total Weapons Qty at the

(high) value of (6 Howitzers / * EFSS) had almost as good an OFOM as the factors just mentioned. This result suggested that for a GCS operation such as the one simulated, the most effective way to reduce total fuel used and increase the percentage of targets neutralized would be to decrease the Threat value to a low threat. A more practical solution would be to position the assets a short distance from the shore, in this case 10 NM, and transit the assets by sea.

For the GCS #8 Metamodel *Blue Casualty*, the factor Threat at the (low) threat value had the largest effect of decreasing the percentage of blue force assets destroyed. On the other hand, the factor Threat at the (high) threat value had the largest effect of increasing the percentage of blue force assets destroyed.

Considering the combined effects of the GCS #1 Metamodel *Total Fuel Used* and the GCS #8 Metamodel *Blue Casualty*, the interaction of the factor Weapon Type at the (M777A2) value and the factor Transit Medium at the (air) value had the best OFOM, providing the combination of factors that most influence total fuel used and average blue force assets lost during the MEU operation. This suggested that for a GCS operation such as the one simulated, the use of the M777A2 transferred by air would have the largest positive effect on mission success.

For the GCS #10 Metamodel *Mission Success*, the factor Threat at the (low) threat value had the largest effect on increasing mission success and conversely the factor Threat at the (high) value of threat had the largest effect on decreasing mission success. Transit Medium at the (sea) value also had a large negative effect on mission success. Conversely, Transit Medium at the (air) value had a large positive effect on mission success.

Considering the combined effects of the GCS #1 Metamodel *Total Fuel Used* and the GCS #10 Metamodel *Mission Success*, the factor Ship2Shore Dist at the (near) value of 10 NM had the best OFOM, providing the combination of factors that most influence total fuel used and mission success of the MEU operation. This was closely followed by the factor Weapon Type at the (EFSS) value. These results suggested that for a GCS operation such as the one simulated, the largest potential for mission success would be

one where the mission was positioned close to shore, in this case 10 NM, and utilized the EFSS weapon system.

12. Metamodel Summary — CAS and GCS

Overall, the largest effect on total fuel used, for both the CAS and GCS scenarios, was from the factor Ship2Shore Dist. This suggested for the two scenarios simulated, the rather intuitive conclusion that less total fuel would be used by positioning the assets close to the shore line or staging point.

For the CAS scenario, the interaction between the factor Total Asset Qty and the factor Assets per Launch had a significant effect on both the MOP 4 — Percentage of Targets Neutralized and the mission success metric. Another interaction, between the factor Ship2Shore Dist and the factor Total Asset Qty had a significant effect on MOP 5 — Percentage of Blue Force Assets Destroyed and the mission success metric. The fact that these factor and factor interactions where all part of the top three OFOM's suggested that for the CAS scenario simulated, increasing the number of types of assets used to 115% of current doctrine and increasing the number of assets launched to 150% of current doctrine, was an effective way to reduce total fuel used and increase mission success.

For the GCS scenario, the interaction of the factor Weapon Type at the value of the (M777A2) asset and the factor Transit Medium at the value of (air), significantly affected MOP 6 — Length of Mission and the MOP 7 — Percentage of Blue Force Assets Destroyed. This suggested that for the scenario simulated, transferring the M777A2 by air was one of the more effective ways to reduce total fuel used while minimizing mission time and percentage of blue force assets destroyed. Another observation was that the EFSS weapon system had the largest effect of increasing mission success.

13. Metamodel Prediction of Fuel Usage and Operational Effectiveness

In the previous section, factors were analyzed in terms of their potential impact or effect on the value of the MOP predicted by the corresponding metamodel. For the CAS

scenario, specific factors or the interaction of specific factors were identified for MOP 1, 3, 4, and 5, along with the metric mission success. For the GCS scenario, specific factors or the interaction of specific factors were identified for MOP 1, 6, 7, and 8, along with the metric for mission success. The following analysis was conducted using the metamodels, specifically the total fuel used metamodel and the mission success metamodel, to develop an efficient frontier plot of potential changes to operational doctrine and the corresponding fuel usage.

For the CAS scenario, mission success was compared to the total fuel used as predicted by the CAS #1 and CAS#9 metamodels. As shown in Figure 53, a comparison was made looking at the effect of a doctrinal change to Assets per Launch. As shown, when at the 150% of current doctrine, a change of Ship2Shore Dist from 60 NM to 100 NM while using a total asset quantity at 115%, results in about a 30% increase in fuel used, but with no sacrifice in mission success. A similar effect was evident while at the Assets per Launch of 50% of current doctrine. Also evident, was the effect of reduced mission success when decreasing the Assets per Launch from 150% to 50%, with all other factors held constant.

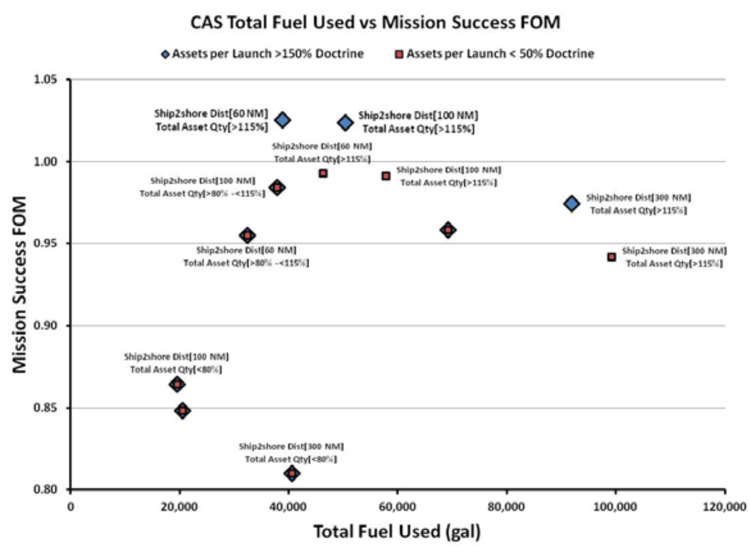

Figure 53. Effect of Doctrine Change to Assets per Launch

Once the dominant combination of factors for both total fuel used and mission success were identified, an analysis was conducted to predict the total fuel used and resulting mission success that would occur due to changes in either doctrine or materiel used during the MEU operation. For the CAS scenario, the dominant combination of factors was used to assess total fuel used and mission success as a result of increasing the number of assets launched to 150% of current doctrine (doctrine change) and the distance to shore (doctrine change). As shown in Figure 54, significant improvement in mission success could be achieved by increasing the number of assets per type to 115% of current doctrine. For distances to shore of 60 NM and 100 NM, significant increases in mission success were predicted with a resulting increase in total fuel used of 20% and 30%, respectively. However, at 300 NM, the increase in mission success was relatively minor even though the increase in total fuel used was still 30%.

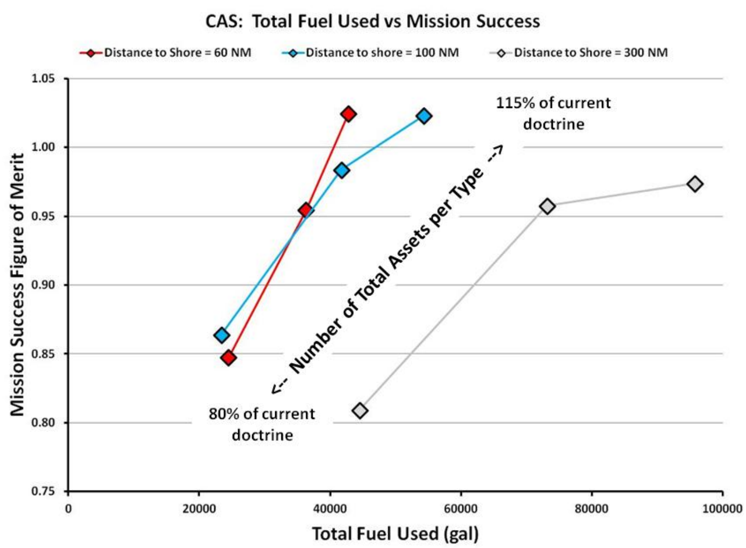

Figure 54. CAS — Total Fuel Used vs. Mission Success: Using Number of Assets Launched = 50% of Current Doctrine

For the GCS scenario, mission success was also compared to the total fuel used as predicted by the GCS #1 and GCS CAS#10 metamodels. As shown in Figure 55, a general trend was evident where the mission success decreased and fuel usage increased as the use of the weapon type went from the M777A2 to the EFSS, to finally the use of

both weapon types combined. Another observation was for a Ship2Shore Dist of 75 NM, the increase in weapon quantity from 4 Howitzers / 4 EFSS to 6 Howitzers / 8 EFSS, had little impact on mission success, but did result in an increase in total fuel used of about 10%.

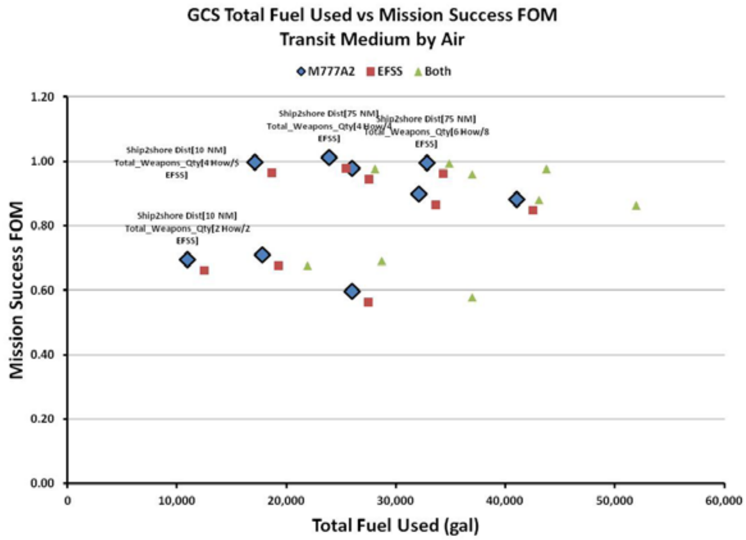

Figure 55. Mission Success and Total Fuel Used of Artillery Asset Variation

For the GCS scenario, the dominant combination of factors was used to assess total fuel used and mission success as a result of changing the weapon type (materiel solution) and distance to shore (doctrine change) while transiting by air. As shown in Figure 56, for each weapon type, increases in the distance to shore resulted in modest increases (generally 20%) in total fuel used with generally less than a 10% decrease in mission success. Also shown was that increasing the quantity of transit mediums per launch to a value of nine significantly increased mission success while generating the lowest total fuel used for each combination of weapon type and distance to shore. More importantly was the effect of the use of the weapon type M777A2, which provided the best mission success at the least amount of total fuel used, regardless of distance to shore and quantity of transit mediums per launch.

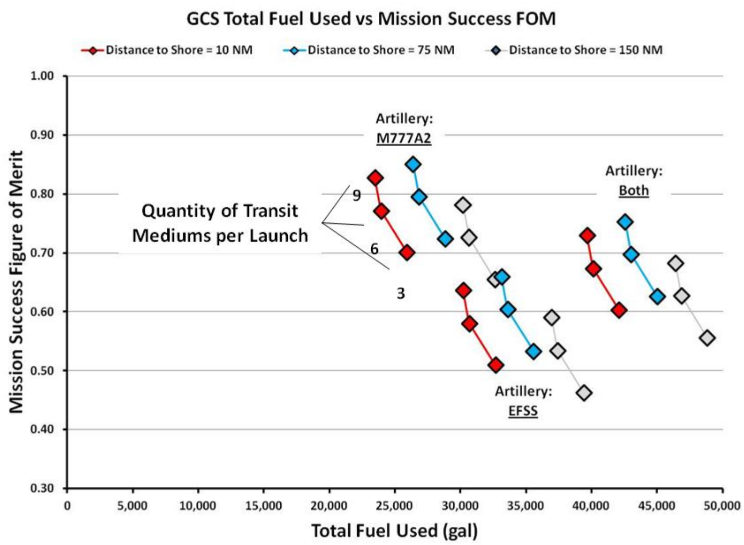

Figure 56. GCS — Total Fuel Used vs. Mission Success: Using Air Transit Medium

D. MISSION SUCCESS

The mission success metamodels developed above were based on a calculated mission success value from each of the ExtendSim simulation model runs. For each ExtendSim simulation model run, mission success was calculated using the predicted value for Targets Neutralized, Blue Force Assets Destroyed, and the Mission Time MOPs. Average values were obtained for these MOPs from the 136 CAS simulation runs and the 170 GCS simulation runs and a comparison of the results discussed below.

A comparison of CAS and GCS successful missions is shown in Table 54. The table identifies four metrics and metric criteria that were used as a measure of mission success in each of the models. In each of the metrics, it is clearly evident that the air model was more successful than the ground model. Of particular note, fuel consumption was not selected as a metric based on the relationship between mission success and operational effectiveness. Fuel consumption is a byproduct of operational effectiveness, but is not a determining factor in the success of a mission.

Table 54. CAS and GCS Mission Success

Metric	Air Model		Ground Model	
	Mission Success Criteria	Average Result	Mission Success Criteria	Average Result
Targets Neutralized (MOP 4&7)	≥ 90%	95.3%	≥ 20%	21.1%
Blue Force Casualties (MOP 5&8)	≤ 2%	1.2%	≤ 50%	56.7%
Mission Time (MOP 2,3&6)	≤ 480 min	416.1 min	≤ 780 min	612.0 min
Successful Missions	71%		36%	

The analysis of the targets neutralized metric indicated a clear disparity in values between the two models. Given the consistent target set in each of the models, the disparity is likely attributed to the effects achieved by the munitions delivered from each platform. Current air munitions are primarily designed to have concentrated effects against relatively small target areas while artillery munitions generally achieve suppression by destructive effects against a similar target set. Based on the targets utilized in the model, for example tanks, the air munitions demonstrated a high percentage of successful effects while artillery munitions resulted in a much lower percentage of desired effects.

Blue force casualties are a critical component to mission success based on the foundational principles of war. When comparing the models according to this metric of mission success, the air model resulted in only 2% blue casualties while the ground model incurred 50% blue force casualties. While not uncommon based on recent historical battles, the target set utilized in the model is not a near-peer competitor. The models used an assumption that friendly forces obtained air superiority and that only two of the nine enemy assets posed a threat to friendly air assets. Additionally, the manner in which aircraft are employed is significantly different than ground fire support assets. Air assets do not have the ability to self-recover without deploying additional resources and effective fires on friendly aircraft typically result in catastrophic results. Comparatively,

ground forces faced threats from seven of the nine enemy assets in the models. While this naturally incurred more casualties for the friendly ground forces, they are also much more capable of self-recovering and capable of withstanding greater casualties before requiring additional assets. The selection of targets used in the models were a primary factor in the disparity of blue force casualties between the two models.

A commander is likely to relate mission time to mission success based on a number of factors such as sustainability and achieving the element of surprise. The mission time metric again favored the air model over the ground model with the greatest disparity of mission time being 300 minutes in one of the simulation runs. The missions in the air models took 416 minutes on average whereas the ground fire support assets took 555 minutes on average to complete the mission. The disparity between the two models is likely attributed to the transit time from the ship-to-shore or ship-to-staging area since the air assets were able to rapidly arrive at the target area and the sea transport platforms move significantly slower, especially in higher sea states.

The final metric used to assess mission success is the percent of successful missions. The ground model only achieved success in 36% of missions while the air model achieved 71%. As mentioned with respect to the targets neutralized, the ground model likely had more unrealistic scenarios based on weapon system type, quantity, and munitions. An example of this is having two EFSS assets attempting to engage a high level threat. Additionally, the artillery munitions selected in the ground model are consistent with current inventories. However, it also highlights a current munitions gap that the artillery community is experiencing due to cluster munitions restrictions resulting from the 2008 Convention on Cluster Munitions Treaty. Development of a more humane munition while still achieving the effects necessary to engage targets such as tanks, could increase the effectiveness of the ground fire support assets.

Overall, the metrics utilized in determining mission success facilitate the greater discussion on fuel consumption. A commander is almost certain not to sacrifice mission success for fuel consumption, but it is important to consider asset allocation with respect to fuel consumption so long as the mission success is still achieved according to the metrics described.

E. SUMMARY

Utilization of an appropriate experimental design strategy allowed for comparative analytics between overall MEU operations. The factor composites shown in Table 55 were found to provide the three most desired states of operations. As will be examined in the next section, recommendations to doctrine and materiel can be made that will reduce fuel usage while maintaining or increasing operational effectiveness.

Table 55. Factor Composites

Factor	Total Fuel	Weapons Used	% Neutralization
Aircraft Type	AV-8B	F-35B	F-35B
Loadout	Option 2	Option 2	Option 2
Temperature	Hot	Cold	Average
Sea State	Calm	Choppy	Calm
Clouds	Mid	Low	Mid
Ship2Shore Dist	Near	Far	Far
Total Asset Qty	Low	Low	High
Assets per Launch	Low	Low	Average
Threat	High	High	Medium

VII. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY

Conclusions were drawn for each research question based on the data obtained from the CAS and GCS ExtendSim models and the analysis performed.

1. Research Question One Discussion

Without sacrificing operational effectiveness, what specific changes of the Marine Corps DOTMLPF could improve fuel usage during a ship-to-shore MEU operation?

<u>DOE Assessment</u>: For the CAS scenario, the analysis of the metamodel Total Fuel Used suggested that the factor Ship2Shore Dist at the (far) value of 300 NM had the largest effect of increasing the total fuel used during the MEU operation. This was followed closely by changing the Total Asset Qty to 115% of current doctrine. Changing the Total Asset Qty to 80% of current doctrine had the largest effect of decreasing the total fuel used, which was followed closely by decreasing the Ship2shore Dist to a (near) value of 60 NM.

Considering the combined effect with the CAS metamodel Average Mission Time, changing the Total Asset Qty to 80% of current doctrine provided the best impact to both total fuel used and average mission time for the MEU operation. Considering the combined effect with the CAS metamodel Targets Neutralized, the factor interaction of Total Asset Qty at the (high) value of 115% of current doctrine interacting with Assets per Launch at the (high) value of 150% of current doctrine had the best impact to both total fuel used and percentage of targets neutralized during the MEU operation. Considering the combined effect of the CAS metamodel Blue Casualty, changing Ship2Shore Dist to the (avg) value of 100 NM provided the best impact to both total fuel used and percentage of blue force assets destroyed during the MEU operation. Considering the combined effect of the CAS Metamodel Mission Success, the factor interaction of Total Asset Qty at the (high) value of 115% of current doctrine and Assets per Launch at the (high) value of 150% of current doctrine provided the best impact to both total fuel used and mission success of the MEU operation.

For the GCS scenario, the analysis of the metamodel Total Fuel Used suggested that the factor Transit Medium at the (air) value provided the best impact to both total fuel used and average mission time of the MEU operation. Considering the combined effects of the GCS metamodel Targets Neutralized, the factor Threat at the (low) threat value provided the best impact to both total fuel used and percentage of target neutralized during the MEU operation. Considering the combined effects of the GCS metamodel Blue Casualty, the interaction of the factor Weapon Type at the (M777A2) value and the factor Transit Medium at the (air) value provided the best impact to both total fuel used and percentage of blue force assets destroyed during the MEU operation. Considering the combined effects of the GCS metamodel Mission Success, the factor Ship2Shore Dist at the (near) value of 10 NM provided the best impact to both total fuel used and mission success of the MEU operation.

<u>Statistical Assessment</u>: The DOE used in this study provided specific options to change DOTMLPF in order to change fuel usage without sacrificing operational effectiveness. First, specific DOTMPLF changes to logistical capability was put through additional statistical analysis and determined a materiel change to the CH-53K would yield greater operational capability with a minimal increase to total fuel consumption.

The in-development CH-53K was compared to the MV-22B. Of note, the CH-53K was not at the flight test stage of development at the time of writing. The CH-53K is advertised to provide more lift capability while consuming the same amount of fuel as the CH-53E, while also advertised to have higher cruise speed at this fuel burn rate. (Sikorsky 2015).Given the mean fuel rates over 136 runs, it was found that the CH-53K has a statistically significant increase in overall fuel usage of 6%. Taken in conjunction with the increased lift capacity of 35,000 pounds versus the MV-22B lift capacity of 20,000 pounds, an increase of 75%, the extra fuel proves to be operationally beneficial. Provided flight tests validate the design of the CH-53K, it will be a significant change in doctrine for MEU’s.

Close air support doctrine was assessed through comparing the fuel usage and operational effectiveness of the F-35B and AV-8B. Additionally, materiel changes in

weapons systems were assessed. Fuel metrics were analyzed through the same two and one tailed t-test between the F-35B and the AV-8B.

Fuel usage was found to be statistically significantly higher for the F-35B across all factors with an average increase of 33% over the AV-8B. In order to determine if this change to doctrine will be beneficial over time, the employment characteristic between platforms was assessed in Table 56.

Table 56. Assessment of Employment Characteristics

	AV-8B High Threat	F-35 High Threat	AV-8B Med Threat	F-35 Med Threat	AV-8B Low Threat	F-35 Low Threat
Average Threat Neutralization	90%	92%	96%	95%	99%	100%
Standard Deviation	15%	13%	8%	10%	2%	1%
t-test p-value	0.689		0.7087		.00394	

As noted in earlier sections, the actual Pd for the F-35B is classified; therefore, all that can be concluded from this analysis is that there is no degradation of operational capability transitioning to the F-35B. Further classified analysis could yield an accurate measurement of increased threat neutralization expectation versus fuel consumption.

One materiel solution that did show change was the weapons systems. Table 57 shows that in a medium threat scenario, utilizing GBU-54’s from AV-8B’s or GBU-53/B’s from F-35B’s will yield more effective results.

Table 57. Medium Threat Scenario Results

	AV-8B high Opt1	AV-8B high Opt2	AV-8B med Opt1	AV-8B med Opt2	AV-8B low Opt1	AV-8B low Opt2
Average Threat Neutralization	91%	90%	92%	98%	99%	100%
Standard Deviation	17%	14%	11%	3%	2%	0%
t-test p-value	0.8798		0.0717		0.1127	
	F-35 high Opt 1	F-35 high Opt 2	F-35 med Opt 1	F-35 med Opt 2	F-35 low Opt1	F-35 low Opt2
Average Threat Neutralization	91%	94%	91%	99%	100%	100%
Standard Deviation	16%	9%	12%	1%	1%	1%
t-test p-value	0.5809		0.0492		0.9875	

Coupled with the conclusions drawn in previous sections with total fuel correlated with ship-to-shore distance, the most effective means to reduce fuel use while maintaining operational capability in a permissive amphibious assault environment is to move the ships closer, utilize CH-53K's and F-35B's equipped with GBU-53/B, varying the tactic (Assets per Launch) to the threat level.

2. Research Question Two Discussion

What effect does a change in materiel solution and doctrine during a ship-to-shore operation have? Which factor or combination of factors provides the greatest decrease in fuel usage without sacrificing operational effectiveness?

<u>DOE Assessment</u>: For the CAS scenario, the biggest doctrine change to MOP 1 Fuel consumption was due to the choice of Ship2Shore Dist at the (far) position of 300 NM, which resulted in an average increase of 48% in total fuel used. The biggest doctrine change to MOP 3 Mission Time was due to the choice of Assets per Launch at the (high)

value of 150% of current doctrine, which resulted in an average decrease of 9% in average mission time. The biggest doctrine change to the mission success metric was due to the interaction of the factor Total Asset Qty at the (high) value of 115% of current doctrine and the factor Assets per Launch at the (high) value of 150% of current doctrine, which resulted in an average decrease of 12% in mission success of the MEU. The interaction of the factor Total Asset Qty at the (high) value of 115% of current doctrine and the factor Assets per Launch at the (low) value of 50% of current doctrine, resulted in an average increase of 11% in mission success of the MEU.

For the CAS scenario, mission success was compared to the total fuel used in terms of the effect of a doctrinal change to Assets per Launch. The analysis showed that when at the 150% of current doctrine, a change of Ship2Shore Dist from 150 NM to 60 NM while using a total asset quantity at 115%, resulted in a 30% increase in fuel used, but with no sacrifice in mission success. A similar effect was evident while using Assets per Launch at 50% of current doctrine. A general trend also noticed was the effect of reduced mission success when decreasing the Assets per Launch from 150% to 50%, with all other factors held constant. For the GCS scenario, mission success was also compared to the total fuel used. Generally, mission success decreased and fuel usage increased as the use of the weapon type went from the M777A2 to the EFSS, to finally the use of both weapon types combined. Another observation made was for a Ship2Shore Dist of 75 NM, where the increase in weapon quantity from 4 Howitzers / 4 EFSS to 6 Howitzers / 8 EFSS, had little impact on mission success, but resulted in an increase in total fuel used of about 10%.

For the CAS and GCS scenarios, the analysis showed that the effect of Ship2Shore Dist generated the biggest impact on fuel usage. For the CAS scenario, when at the 150% of current doctrine, a change of Ship2Shore Dist from 150 NM to 60 NM while using a total asset quantity at 115%, resulted in a 30% decrease in fuel used, but with no sacrifice in mission success. A similar effect was predicted for the GCS scenario, where a change in Ship2Shore Dist from 75 NM to 10 NM, while using the weapon quantity of 4 Howitzers / 4 EFSS being transited by air, resulted in a 38% decrease in total fuel used, also with no significant degradation in mission success.

3. Research Question Three Discussion

Can a discrete event simulation of an MEU ship-to-shore operational scenario to provide close air support capture realistic improvements in fuel usage due to changes in aircraft materiel solution (F-35B versus AV-8B) and doctrine (total asset quantity and assets per launch)?

a. Ease of Modeling and Simulation

Significant time was required in order to build a discrete model in ExtendSim that can capture all the details of MEU operations. Fuel usage for a single air asset during transit to and from the mission area was modeled. However, modeling fuel usage of multiple air assets was complicated. An example is when coordinating takeoff sequence, takeoff delay, and staging of air assets while the rest of the flight takes off. It was challenging coordinating the actions of all the blue and red assets to accurately model fuel usage and engagement outcome of a CAS mission.

An agent-based modeling tool may be better suited in capturing all the details of MEU operations. Each blue and red asset can be modeled as individual agents with specific reactions to certain stimulus. In a CAS mission, for example, a blue agent could be modeled to attack a red agent based on distance, target priority, cloud coverage, and available munition. A red agent could be modeled to evade or counter-attack an attacking blue agent based on distance, cloud coverage, and available munition. Simulating blue and red agent interactions becomes trivial once the blue and red agents' behavior has been modeled. In contrast, discrete event simulation must coordinate all blue and red asset interactions.

b. Results

For the CAS scenarios, the use of the discrete event simulation did not capture any potential improvements to changing from the AV-8B to the F-35B. The analysis showed there was little effect from this change on any of the MOPs considered. In each of the metamodels developed, none had Aircraft Type as a top ten factor effecting the MOP being predicted. Whether this was a result of the way in which these assets where

modeled or a due to inaccurate aircraft performance data, was not known at this time. For the total asset quantity and Assets per Launch factors, the discrete event simulation of the CAS scenario clearly identified realistic improvements in current doctrine. For the CAS scenario, when at the 150% of current doctrine, a change of Ship2Shore Dist from 150 NM to 60 NM while using a total asset quantity at 115%, resulted in a 30% decrease in fuel used, but with no sacrifice in mission success.

While some details can be extracted from this projects model, not all of the goals could be effectively or accurately depicted. Blue force losses were inaccurate due to classification boundary restrictions. Weapons effectiveness could be proportionally modeled, but not to real-world specifications.

The model was able to produce recommended changes to doctrine and materiels. Utilizing the F-35B, with new weapons systems in traditional force strength will yield better operational effectiveness with the same or less fuel usage. Further analysis, recommended at the classified level, will be able to evaluate a real world quantitative fuel usage amount.

4. Research Question Four Discussion

Can a discrete event simulation of an MEU ship-to-shore operational scenario to provide artillery support capture realistic improvements in fuel usage due to changes in artillery materiel solution (Expeditionary Fire Support System versus M777A2 howitzer) and doctrine (assets per launch and shore-to-staging distance)?

a. Ease of Modeling and Simulation

Similar to the CAS model, the GCS fuel usage and target engagement was challenging when the actions of all the blue and red assets were coordinated. To simplify the GCS model, it was assumed that the red assets counter-attacked when they were attacked by a blue assets. The model did not take into account the distance between the blue and red assets which would significantly affect the outcome of the engagement.

Agent-based modeling tools may provide a more accurate model of the GCS fuel usage and target engagement. Just like the CAS model, a blue GCS asset's behavior

could be modeled using an agent-based modeling tool to engage a red asset based on distance, target priority, and available munition. The red GCS asset's behavior could be modeled to engage the attacking blue asset based on distance, terrain, and available munition. As with the CAS model, simulating GCS blue and red asset interaction becomes trivial once the behaviors for the blue and red assets has been modeled.

b. Results

For the GCS scenario, the use of a discrete event simulation captured realistic improvements to fuel usage. Generally, mission success decreased and fuel usage increased as the use of the weapon type went from the M777A2 to the EFSS, to finally the use of both weapon types combined. Another observation made was for a Ship2Shore Dist of 75 NM, where the increase in weapon quantity from 4 Howitzers / 4 EFSS to 6 Howitzers / 8 EFSS, had little impact on mission success, but resulted in an increase in total fuel used of about 10%. For the GCS scenarios, the use of the discrete event simulation did not capture any potential improvements to changing the shore to fire position distance. The analysis showed there was little effect from this change on any of the MOPs considered. In each of the metamodels developed, none had shore to fire position distance as a top ten factor effecting the MOP being predicted. This was most likely due to the relatively small amount of fuel used during this phase of the scenario, and less from the way it was modeled in the simulation.

B. CONCLUSIONS

The boundary limits for the project, described in previous sections, proved to limit the ability to answer all of the research questions. DOTMPLF change recommendations in doctrine and materiel were extracted, and current tactics were validated, but generating a specific fuel metric to evaluate operational effectiveness could not be determined. Additional research, preferably at the classified level, would further investigation into a fuel metric tied to operational effectiveness, the total fuel consumed, total weapon usage and neutralization rate. Additional research using models for a QRF, combined CAS and GCS scenario, and for an evolving threat are recommended future efforts.

C. RECOMMENDATIONS

There are several areas that could be pursued to build upon the efforts performed in the capstone project and the results from the data analysis performed. Some efforts could not be accomplished during this capstone project and would be recommended as future efforts to continue with model development. Other efforts are areas of interest that arose once data analysis was performed using the CAS simulation data.

1. QRF Model Development

During this capstone project the architectural framework was developed and fuel consumption data was collected for the quick reaction force (QRF) maneuvers. However, an ExtendSim model was unable to be developed for a QRF. An ExtendSim model for the CAS and GCS scenarios provides a framework for future work relating to a QRF scenario. The current organizational structure for an MEU comprises of both air and sea lift capabilities in order to bring Marines ashore. This framework enables the modeling of each asset and the varying conditions it may experience in order to appropriately evaluate the fuel consumption and ultimately assess potential modifications to current structure.

The QRF scenario is of particular importance not just because of the severity of the mission, but also due to the variety of options with respect to unit needing assistance and platform delivering the reaction force. While air delivery of the force is primary, it is also possible that assistance may be needed when air is unable to launch. It is recommended that future work explore all variants (current and future) models of the CH-53, the MV-22 Osprey, and well as landing crafts.

In order to compare the results from the QRF scenario to the CAS and GCS scenarios it is recommended that the BMP-2 platoon be modeled as a threat. Although the threat was only present in the CAS scenario, this threat should have been present in all models.

2. Combined CAS and GCS Model Development

In a typical MEU response both ground and air assets would be used, instead of solely one or the other. Creating a comprehensive model that simulated the combined

interactions with CAS and GCS would provide a more realistic level of fidelity to a battle engagement scenario. This model would facilitate a realistic approach to achieving the operational effectiveness while at the same time assessing the fuel use by the varying assets. Commonly, aviation assets consume a significant amount of fuel and therefore, their integration into the entire MEU response would evaluate potential deviations from current doctrine or procedures.

The combined battle engagement scenario includes an integrated air and ground attack engagement. The integrated attack also consists of three phases and begins with the commander identifying the threat and considering decision variables such as force structure and ammunition load out. The first scenario of this vignette simulates the use of AV-8Bs, AH-1Zs/UH-1Ys, M777A2 howitzers, and EFSS. The second scenario of this vignette simulates the use of F-35Bs, AH-1Zs/UH-1Ys, M777A2 howitzers, and EFSS. The ground attack platforms are transported either by sea transport or by air transport and then must debark and move to the position area for artillery in preparation for engagement while the CAS platform launches from the ship to a planned pre-positioning location in preparation for engagement. The ground and air platforms engage the target sets of low, medium, and high threat level. If the effects are not achieved, then re-attack is executed by either the air or ground platform. Upon successful engagement of the target set, the ground platforms move from the objective to the shore and embark while the CAS platforms return to the ship. The scenario concludes with all platforms returned to the ships.

Another important factor to consider in the integrated model is the selection of a target set for the friendly forces. A MEU is organized in such a manner that it is likely not going to be engaged in a heavy conflict or without some element of preparatory fires. The air and ground models used this assumption, explaining the assumption for air superiority throughout the model. However, when facing a near-peer enemy, this assumption cannot be made and should be considered in the model. Other assets outside of the MEU will likely attempt to eliminate surface-to-air or air-to-air threats, but the risk would increase.

Analysis of the ground model attributed the target set as the primary factor in the GCS achieving significantly inferior values compared to the air model. Another consideration for the ground model would be to expand or modify the target set so that it includes targets favorable for both air and ground fire support assets. This would include larger formations of infantry or command and control posts more favorable to artillery munitions to be more within the realm of a likely enemy. The integrated model could include a balanced set of targets that demonstrate the capabilities of the different weapon systems. However, the most important factor in constructing the appropriate target set is to use the most likely enemy formation that a MEU would face in the future.

3. An Adaptive Framework for Evolving Threats

The architectural framework constructed during this capstone for a conventional MEU construct could serve valuable for future USMC efforts. As described in Expeditionary Force 21, the proliferation of adversary target acquisition and guidance systems requires standoff of at least 65 nautical miles (*Expeditionary Force 21* 2014a). This range is greater than five times the current position for ships during the launching of aircraft or ships ashore. Further indications within Expeditionary Force 21 state that this range will continue to increase with increasing technology. The architectural framework created in this capstone project and the models utilized could serve as a stepping stone for the analysis of fuel consumption in the new scenarios. The assets, equipment, and procedures are likely to be altered in order to counter the current and future threats. The positioning of ships further from shore will naturally have a substantial impact on the fuel consumed by both air and sea crafts and should be evaluated.

Additional research in the recommended areas will facilitate the optimization of both operational effectiveness and fuel efficiency. While it is unlikely that the military would sacrifice mission success for fuel savings, additional research with respect to the future vision of the U.S. Marine Corps and U.S. Navy as it pertains to MEU employment is important because maximization of both can be achieved. Historically, employment of the MEU has been primarily focused on achieving mission success regardless of the second order effects, such as energy. Using this model as a framework can couple both

fuel efficiency considerations and new strategic employment of the MEU to provide a more streamlined and overall efficient fighting force.

APPENDIX A. LITERATURE RESEARCH

This appendix provides the detailed literature review of the references used in the problem definition.

A. 2014 CAPSTONE REPORT (BENNETT ET AL. 2014)

1. Summary

In the 2014 capstone project, the following four research questions were posed:

- What is the energy cost associated with execution of a successful USMC expeditionary mission, where the measures of success are determined by operational effectiveness?
- What are the impacts of variations in MEB scaling on operational effectiveness and operational energy?
- What is the USMC operational energy trajectory with regards to the trade space between effectiveness, energy, and other measures as defined by USMC doctrine from the Expeditionary Energy Office?

The 2014 capstone project focused on establishing the relationship between energy demand and MEB size in the context of a successful USMC expeditionary mission. Specifically, the 2014 capstone project evaluated operational energy efficiencies associated with force scale alternatives of a Special Purpose Marine Air Ground Task Force (SPMAGTF) unit operating in the West Africa area of responsibility. The mission included an Air Combat Element (ACE) providing maneuver insertion and combat support to a Ground Combat Element (GCE) pursuing a direct fires engagement.

The project identified several measures of effectiveness (MOE) and corresponding threshold values that were required for mission success. MOEs included Quick Reaction Force Reaction Time, Percent of Targets Attacked with Desired Effects, and Percent of Casualty Death to name a few. A mission was considered successful if all critical MOEs and at least 50% of non-critical MOEs were met.

The project developed a Map Aware Non-Uniform Automata (MANA) model for each SPMAGTF size. The MANA models simulated the maneuver and direct fires missions associated with the West Africa area scenario. Spreadsheet techniques were used to augment the GCE modeling and to provide a basis for analyzing energy

dependencies between the battle engagement and the ACE supporting elements. Data for battle engagement parameters such as Blue Injured, Blue Dead, Red Injured, Red dead, and Battle Length were predicted by the MANA model. Data for fuel usage parameters such as Remaining Fuel-HMMWV, Remaining Fuel-CH-53K, and Remaining Fuel-MV-22 were also predicted as part of the MANA model. Results from the model were used to determine the value obtained for each MOE.

The team found that all three force scale alternatives (platoon levels) resulted in successful missions, so no conclusions were inferred about threshold success level. The following describes several of the key energy demand results from the project.

- The 3-Platoon level had the lowest total fuel usage, however, the 4-Platoon level offered the lowest casualty rate and second best Loss Exchange Ratio (LER) (Blue over Red) for a modest increase in fuel usage. If injuries were added to the LER, the ratio becomes much higher due to high Blue injury rates, an artifact most likely from the lack of Tactics, Techniques, and Procedures (TTP) and Situational Awareness (SA) used in the MANA model.
- In terms of battle length, the 4-Platoon level was dominant over the 5-Platton level and offered superior effectiveness over the 3-Platoon level for a marginal increase in fuel usage.
- For Overall Measure of Effectiveness (OMOE), the 4-Platoon level offered the best overall alternative in the study. The 3-Platoon level offered the lowest effectiveness although in terms of effectiveness per fuel use it had a similar result to the 4-Platoon level option.

2. Recommended Future Research Topics

Holistic Mission Modeling. The 2014 capstone project scenario focused on a land based engagement, where Marines were transported to the battle sight using the MV-22, CH-53K, or HMMWV. As described in USMC Expeditionary Force 21, the battle space will be well integrated and utilize elements of air, land, and sea effectively to support the dominance of the enemy (United States Marine Corps 2014). If all three elements where modeled as part of the Barra Vignette, a better understanding of how energy is committed and consumed across the MAGTF and how it relates to effectiveness could emerge.

Net-Centric Modeling. The 2014 capstone project found that Superior Weapons and Armor do not necessarily compensate for an inadequate battle space understanding, which impacts energy. If the incorporation of SA, Command and Control (C2), and

organizational tactics are modeled, a better understanding of the relationship between net-centric warfare and resulting energy efficiencies may result.

Hybrid Modeling. The 2014 capstone project utilized the Agent Based Modeling and Simulation (ABMS) MANA model to predict the operational outcome of the scenario selected. As they described, ABMS allowed exploration of multiple interaction environments with somewhat unknown behavioral outcome. The team realized that the elaborate Concept of Operations (CONOP) associated with the scenario modeled lends itself to combing both the ABMS and a Discrete Event Simulation (DES) approach. The DES approach permits the development of relatively known, low interaction to be modeled. The use of a hybrid approach could provide more insight into the overall study so that both known and unknown behavior can be examined together. However, it was not clear as to how this would be accomplished, but the benefits could be significant.

Behavioral Energy Modeling. The 2014 capstone project proposed the use of behavioral based energy modeling, which energy commitment decision-making affinity factors were introduced. This effort would require an examination of decision making in the battle space, which includes energy committing along with other battle decisions. The approach would investigate the trade space of agent propensities across a behavioral spectrum. Such an effort may result in a useful tool to evaluate warfighting doctrine in light of the Marine Corps present desire to return balance between fast, austere, and lethal.

B. 2013 CAPSTONE REPORT (BESSER ET AL. 2013)

1. Summary

In the 2013 capstone project, the following four research questions were posed:

- What impacts to the FHA/DR mission are experienced due to non-materiel changes?
- What impacts to the FHA/DR mission are experienced due to materiel changes?
- Can any of the changes be combined to provide increased mission success?
- What are the implantation actions needed to adopt promising changes?

The 2013 capstone project used the DES approach to model the behavior and movement of the components of this FHA/DR scenario. Specifically, the software ExtendSim was used to develop the model. The model captured the ground-based transportation element of the FHA/DR including transport time, distance traveled, wait times, water production and supplies delivered. The intent of the model was to capture the operations of the transportation element as well as the impact of adding water purification at various sites as they related to the identified MOEs.

The 2013 capstone project considered the effect of two different types of materiel solutions on overall fuel usage and logistical foot print, water purification systems and vehicle modifications. The first materiel solutions analyzed were water purification systems. The project considered the following two water purification systems: a) Lightweight Water Purification System (LWPS) and b) Tactical Water Purification System (TWPS). Overall, the water purification systems provided significant improvements in most MOEs but when taken to the extreme, resulted in unacceptable increases in personnel requirements. The optimal configuration will be based on the specific mission parameters and distribution sites. While some gross estimates of the best configuration is possible a tailored planning tool could provide a very effective TTP capable of optimizing the mission plan for an MEU. The second materiel solution analyzed was vehicle modifications. The materiel solutions for improving vehicle performance were broken into three major areas, hybrid systems, follower systems, and fully autonomous systems. Each system was further differentiated into high and low-end concepts to represent the wide range of potential solutions. Both follower and hybrid were dominated by the fully autonomous system. The most significant factor in the reduced fuel consumption was the elimination of the habitability needs while idling. Even in a high demand FHA/DR the vehicles continued to see idle times of approximately 50%. When the autonomous system is idling only minimal computer / communication functions are required to be active. In addition the reduced cab and armor weight significantly increases miles per gallon efficiency. Man-hours are the most dramatic MOE change across the vehicle configurations. The baseline scenario utilized over 30,000 man-hours transporting supplies over a 10-day operation. The follower systems

reduced this to 20,000 hours and the autonomous systems to 10,000 hours. These reductions were based on small convoy sizes of three vehicles. Since the lead vehicle is always full manned, larger average convoy sizes would see proportionally improved results.

Lastly the logistical footprint aboard ship was presented more mixed results. The low end hybrid and follower systems both added 0–7% to afloat weight. The high end hybrid had a potential reduction of 7% of weight. The autonomous provided the greatest weight reduction of 10% due to the elimination of the cab and armor requirements. Overall only the introduction of autonomous vehicles dominated across all MOEs and use cases.

The most significant MOE improvements were due to elimination of the underlying needs. This included eliminating the need to idle vehicles by eliminating the manned spaces and armor, eliminating transportation of water by purifying on site, and eliminating drivers by automating driving.

2. 2013 Capstone Future Research Topics

Mission Planning Tool for Water Purification. One significant finding from the study was the sensitivity of the MOEs to the water purification system lay down. While some gross estimates and rules of thumb can be developed to help mission planner an analytical tool capable of optimizing the lay down would significantly improve overall effectiveness. Development of this mission planning tool would be a valuable avenue for future research.

Cost Model. Based upon feedback from the E2O a detailed estimate of the cost savings from fuel consumption was not undertaken. This is due to the highly varied and controversial estimates of the actual cost of transporting fuel if threats and other factors are taken into account. An analytical review of threats and risks along with direct costs of fuel transport would be beneficial in providing a basis for cost analysis and comparison. This cost basis will be necessary for major programmatic decisions concerning new system development.

Computer Reduction. A DOTMLPF analysis and further research on the number of computer assets within the USMC would be beneficial and worthwhile. Computer assets are the number one non-vehicle, non-aviation source of energy consumption. Certification and Accreditation (C&A) policy and information security are the primary drivers for the quantities of computers. A hard look at the policy governing the C&A process, new technology available to secure these assets, and incorporating cloud computing could significantly reduce the number of computers, the energy consumption, and supportability costs. Another source of computer usage is the introduction of portable computing assets. Many programs are fielding laptops solely utilized for logistical and technical publication storage vice issuing a paper copy. A study needs to be initiated to examine the suitability, durability, reliability of commercially available products in a combat environment. Industry also needs to be canvassed to assess possible ruggedized portable assets for military use.

Auxiliary Power Unit (APU) Requirements Development. Preliminary studies have shown that APUs do provide fuel efficiencies at idle but these efficiencies are negated due to the current size of such technologies. The team suggests a future study could be to calculate the maximum sizes, weights, and power outputs required of APUs before fuel efficiencies are lost (i.e., break-even points) for the current inventory of ground vehicles. Defining operationally effective size, weight, and power requirements for APUs is the first step (i.e., systems engineering process input) before such technologies can be evaluated within the systems engineering process. Defined requirements can drive APU technology development or eliminate APUs as suitable materiel solutions if there is no feasible way for such technologies to meet these requirements.

Fuel-Less Water Production. In accordance with the USMC's desire to move to a logistical footprint that only allows fuel for ground-transportation, a look into fuel-less water production provides a viable future research topic. At this time, it is believed that there may be issue with sustaining the quality of water produced by these systems. A combined study or project with USMC, U.S. Environmental Protection Agency (EPA)

and pertinent federal health agencies could help move these systems from a nice thought to a vital reality.

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APPENDIX B. ASSET SIMULATION FLOW

This appendix shows the detailed simulation flow for each asset used in the model. Each figure shows the flow of events from ship-to-shore, engagement, and return for each component of the physical architecture.

A. F-35B / AV-8B MISSION FLOW DIAGRAM

The F-35B / AV-8B will take off and leave the ship in order to complete a close air support mission as shown in Figure 57. Throughout the mission the remaining fuel is monitored as well as the remaining target and munitions remaining in the mission. If there are no munitions or targets remaining the mission is considered complete. If there is no fuel remaining and no tanker nearby the mission is also considered complete.

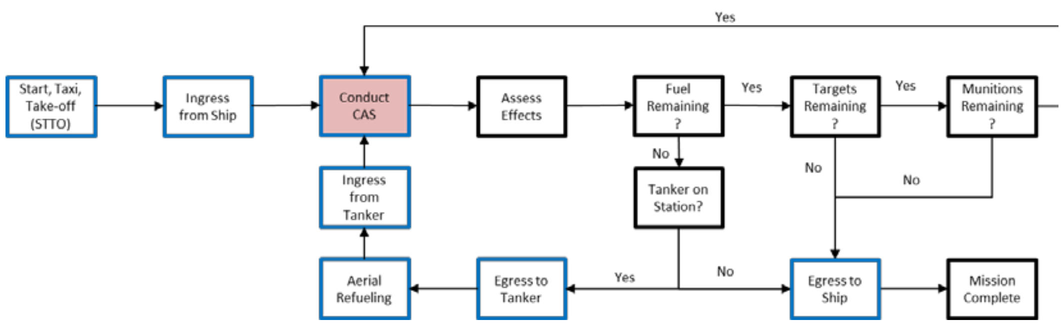

Figure 57. F-35B / AV-8B Mission Flow

B. AH-1 / UH-1 MISSION FLOW DIAGRAM

The AH-1 / UH-1 will take off, hold, and leave the ship in order to conduct a close air support mission as shown in Figure 58. During the mission the amount of fuel, targets, and munitions remaining will be monitored in order to determine when the mission is complete.

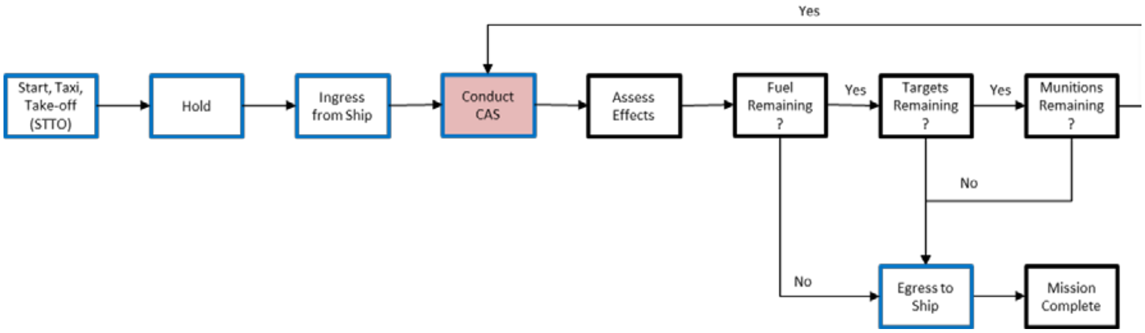

Figure 58. AH-1 / UH-1 Mission Flow

C. CH-53 / MV-22B MISSION FLOW

For the CAS model, the CH-53 / MV-22B were modeled to take off, hold, and leave the ship in order to pick up a payload as shown in Figure 59. During the mission the amount of fuel was monitored to determine when return to ship was needed and when the mission was complete. If a CASEVAC was requested the asset was loaded and returned to the ship and the mission was complete.

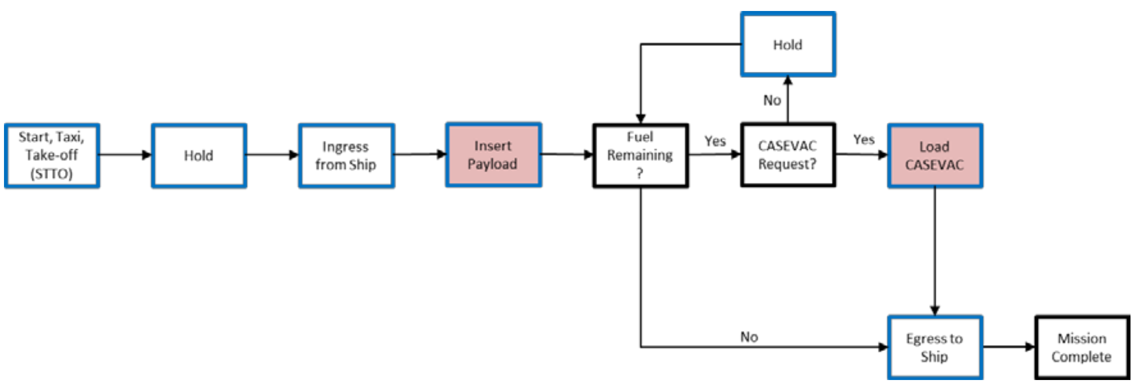

Figure 59. CAS CH-53 / MV-22B Mission Flow

For the GCS model, the CH-53 / MV-22B mission flow is shown in Figure 60. These assets were modeled to take off and transit to the mission area to transport the GCS assets, return to the ship, and transport any remaining GCS assets to the mission. Once the all the GCS assets had been transported, the CH-53 / MV-22B returned to the ship and waited until the target engagement phase was complete. When the target engagement phase was completed, the CH-53 / MV-22B transited to the mission area and transported

the GCS assets back to the ship. The CH-53 / MV-22B returned to the mission area and transported any remaining GCS assets back to the ship until all assets were removed from the mission area.

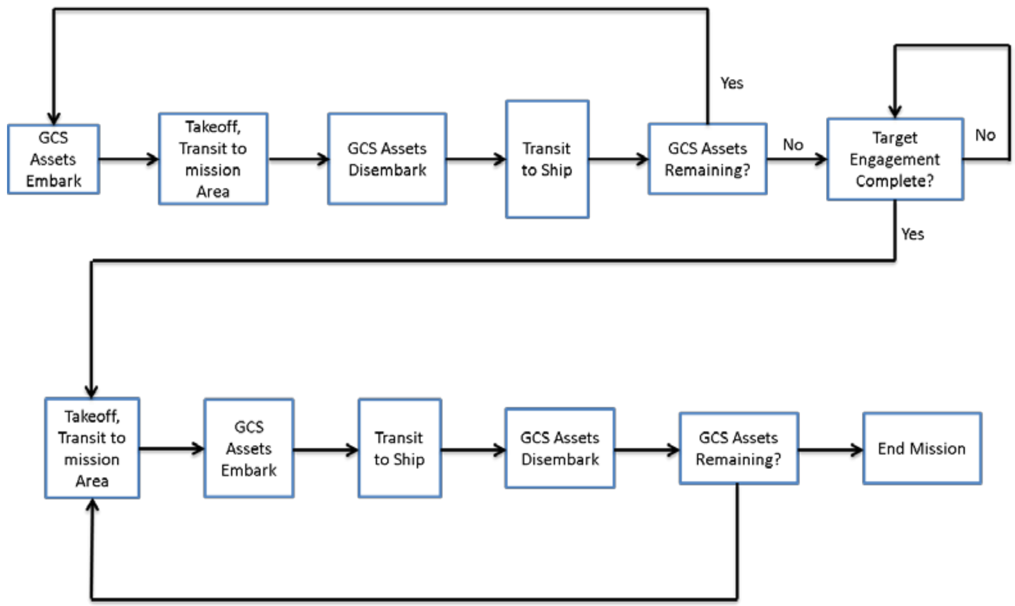

Figure 60. GCS CH-53 / MV-22B Mission Flow

D. LCAC MISSION FLOW

The LCAC mission flow is shown in Figure 61. The LCAC began by transiting to shore with GCS assets. Once on the shore, the GCS assets disembarked and the LCAC transited back to the ship. The LCAC transported any remaining GCS assets to shore and waited until the target engagement phase was completed. The LCAC transited to shore, then the GCS assets embarked and the LCAC transported the GCS assets back to the ship when the target engagement phase was completed. The LCAC transported any remaining GCS assets from the shore back to the ship until all assets were returned.

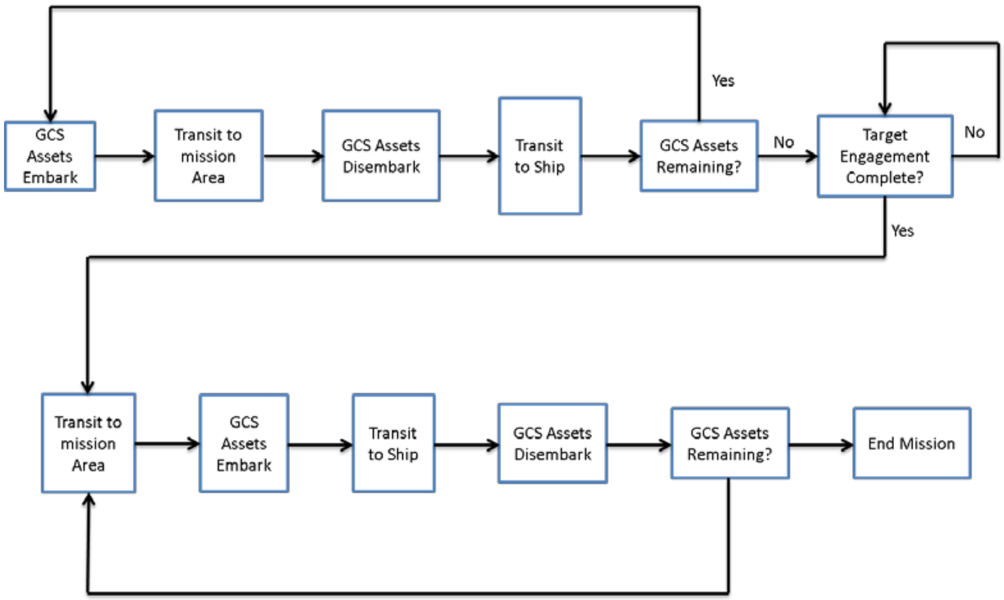

Figure 61. LCAC Mission Flow

APPENDIX C. FACTOR VALUES USED FOR DOE STRATEGY

Custom Design DOE Strategy – CAS Nine Factors

Sim Run #	Aircraft Type	Loadout	Temperature (F)	Sea State	Clouds	Ship2Shore Dist	Total Asset Qty	Assets per Launch	Threat
1	F-35B	Opt1	Hot	Choppy	Clear	Far	High	Avg	Low
2	F-35B	Opt1	Avg	Choppy	Low	Avg	High	Low	Low
3	AV-8B	Opt2	Cold	Choppy	Clear	Avg	Avg	High	High
4	F-35B	Opt1	Avg	Rough	Low	Far	High	High	Med
5	AV-8B	Opt1	Hot	Rough	Low	Avg	Avg	Avg	High
6	AV-8B	Opt2	Cold	Rough	Clear	Far	High	High	Low
7	AV-8B	Opt1	Hot	Choppy	Clear	Near	Avg	Low	High
8	AV-8B	Opt1	Hot	Rough	Mid	Near	High	High	High
9	F-35B	Opt2	Avg	Calm	Clear	Near	Low	Low	Low
10	F-35B	Opt1	Avg	Rough	Clear	Far	Low	High	High
11	F-35B	Opt2	Cold	Calm	Mid	Avg	Low	Low	Low
12	AV-8B	Opt1	Hot	Choppy	Low	Near	High	Avg	Med
13	AV-8B	Opt2	Avg	Calm	Clear	Near	Low	High	High
14	AV-8B	Opt2	Avg	Calm	Clear	Avg	High	Low	Med
15	F-35B	Opt2	Avg	Choppy	Low	Far	Low	High	Low
16	F-35B	Opt1	Hot	Choppy	Clear	Avg	Avg	Avg	Med
17	F-35B	Opt1	Cold	Choppy	Mid	Avg	Avg	Low	High
18	F-35B	Opt1	Hot	Calm	Mid	Far	Avg	Low	Low
19	F-35B	Opt2	Cold	Rough	Low	Far	High	Low	High
20	AV-8B	Opt2	Hot	Calm	Low	Near	High	Low	High
21	F-35B	Opt1	Cold	Rough	Clear	Near	High	Low	Med
22	AV-8B	Opt2	Hot	Choppy	Mid	Near	Low	Low	Low
23	F-35B	Opt2	Hot	Rough	Mid	Near	Avg	Avg	High

Sim Run #	Aircraft Type	Loadout	Temperature (F)	Sea State	Clouds	Ship2Shore Dist	Total Asset Qty	Assets per Launch	Threat
24	F-35B	Opt1	Cold	Choppy	Low	Avg	Low	Avg	Med
25	F-35B	Opt1	Hot	Calm	Mid	Near	Low	Avg	Med
26	AV-8B	Opt2	Cold	Calm	Low	Near	Low	Avg	Med
27	AV-8B	Opt1	Hot	Calm	Low	Avg	Low	Low	Low
28	F-35B	Opt2	Avg	Choppy	Mid	Far	Avg	Low	Low
29	AV-8B	Opt2	Hot	Choppy	Clear	Far	Low	High	Med
30	F-35B	Opt2	Avg	Rough	Clear	Near	High	High	Med
31	AV-8B	Opt1	Cold	Calm	Clear	Avg	Low	High	Med
32	AV-8B	Opt1	Cold	Rough	Low	Avg	High	Low	High
33	AV-8B	Opt1	Hot	Calm	Low	Far	Avg	Avg	Med
34	F-35B	Opt1	Hot	Calm	Clear	Avg	Low	Low	Med
35	F-35B	Opt1	Cold	Calm	Clear	Avg	Avg	Low	Low
36	AV-8B	Opt1	Hot	Choppy	Mid	Avg	Low	High	High
37	AV-8B	Opt1	Avg	Calm	Mid	Far	Low	Avg	Low
38	AV-8B	Opt2	Cold	Choppy	Mid	Avg	High	High	Med
39	AV-8B	Opt1	Avg	Calm	Low	Avg	High	High	High
40	AV-8B	Opt1	Cold	Choppy	Clear	Far	Avg	Low	Med
41	F-35B	Opt2	Cold	Calm	Mid	Near	Avg	Low	Med
42	AV-8B	Opt1	Avg	Rough	Clear	Near	Low	Avg	Med
43	F-35B	Opt1	Cold	Calm	Low	Far	Low	High	High
44	F-35B	Opt1	Hot	Calm	Mid	Avg	High	Avg	High
45	AV-8B	Opt2	Cold	Choppy	Low	Far	High	Avg	Med
46	AV-8B	Opt2	Cold	Choppy	Low	Avg	Low	High	Low
47	AV-8B	Opt1	Avg	Rough	Clear	Far	High	Low	Low
48	F-35B	Opt2	Cold	Rough	Low	Near	Low	High	High
49	AV-8B	Opt2	Cold	Calm	Clear	Far	Low	Low	High
50	F-35B	Opt1	Cold	Rough	Low	Far	Low	Low	Low

Sim Run #	Aircraft Type	Loadout	Temperature (F)	Sea State	Clouds	Ship2Shore Dist	Total Asset Qty	Assets per Launch	Threat
51	AV-8B	Opt2	Avg	Rough	Low	Far	Low	Avg	High
52	AV-8B	Opt2	Hot	Rough	Clear	Avg	High	Avg	High
53	AV-8B	Opt2	Cold	Choppy	Clear	Near	High	Low	High
54	AV-8B	Opt2	Avg	Rough	Mid	Far	Avg	High	Med
55	AV-8B	Opt2	Avg	Choppy	Low	Avg	High	Avg	Low
56	AV-8B	Opt2	Hot	Calm	Mid	Near	High	Avg	Low
57	AV-8B	Opt1	Cold	Choppy	Mid	Avg	High	Avg	Low
58	F-35B	Opt1	Hot	Rough	Clear	Avg	Low	Low	High
59	AV-8B	Opt2	Hot	Calm	Mid	Avg	Low	Avg	Med
60	F-35B	Opt1	Cold	Calm	Mid	Far	High	Low	Med
61	AV-8B	Opt1	Avg	Calm	Mid	Near	Low	Low	Med
62	F-35B	Opt2	Cold	Choppy	Mid	Far	Low	Avg	High
63	F-35B	Opt1	Avg	Calm	Clear	Near	High	Avg	Low
64	AV-8B	Opt1	Cold	Calm	Mid	Near	Avg	High	High
65	AV-8B	Opt1	Avg	Choppy	Clear	Near	High	High	Low
66	F-35B	Opt1	Cold	Choppy	Clear	Avg	High	High	High
67	AV-8B	Opt1	Hot	Calm	Clear	Far	High	High	Med
68	AV-8B	Opt1	Cold	Rough	Mid	Far	Avg	Avg	Low
69	AV-8B	Opt2	Avg	Rough	Low	Near	High	Low	Med
70	F-35B	Opt2	Cold	Rough	Clear	Far	Low	Avg	Med
71	AV-8B	Opt1	Avg	Rough	Mid	Avg	High	Avg	Med
72	F-35B	Opt1	Cold	Choppy	Low	Near	Avg	High	Med
73	F-35B	Opt1	Avg	Calm	Mid	Avg	Avg	Avg	Med
74	F-35B	Opt1	Cold	Rough	Mid	Avg	Avg	High	Med
75	F-35B	Opt2	Avg	Rough	Low	Avg	Avg	High	Low
76	AV-8B	Opt1	Cold	Calm	Clear	Far	High	Avg	High
77	F-35B	Opt2	Hot	Calm	Clear	Far	High	High	High

Sim Run #	Aircraft Type	Loadout	Temperature (F)	Sea State	Clouds	Ship2Shore Dist	Total Asset Qty	Assets per Launch	Threat
78	AV-8B	Opt1	Avg	Choppy	Mid	Near	Avg	Avg	High
79	F-35B	Opt2	Hot	Rough	Mid	Avg	High	Low	Low
80	F-35B	Opt2	Avg	Calm	Clear	Avg	Low	Avg	High
81	AV-8B	Opt2	Cold	Calm	Clear	Near	Avg	Avg	Med
82	F-35B	Opt2	Cold	Choppy	Clear	Far	Avg	High	Med
83	F-35B	Opt2	Cold	Choppy	Clear	Avg	High	Avg	Low
84	AV-8B	Opt2	Cold	Rough	Low	Avg	Avg	Avg	Med
85	AV-8B	Opt1	Cold	Choppy	Low	Near	Low	Low	High
86	F-35B	Opt2	Hot	Rough	Mid	Far	Low	High	Low
87	AV-8B	Opt2	Avg	Rough	Mid	Avg	Low	High	Low
88	F-35B	Opt2	Avg	Choppy	Low	Near	High	High	High
89	AV-8B	Opt2	Hot	Calm	Low	Far	Low	High	High
90	AV-8B	Opt1	Cold	Calm	Low	Far	High	Low	Low
91	F-35B	Opt2	Avg	Calm	Mid	Far	Low	Low	High
92	AV-8B	Opt2	Hot	Choppy	Mid	Near	Avg	High	Med
93	AV-8B	Opt1	Avg	Choppy	Low	Avg	Avg	High	Med
94	AV-8B	Opt2	Avg	Calm	Mid	Far	High	Avg	High
95	AV-8B	Opt2	Avg	Rough	Clear	Avg	Avg	Low	High
96	F-35B	Opt1	Hot	Rough	Clear	Near	Avg	High	Low
97	F-35B	Opt1	Cold	Rough	Clear	Near	Avg	Avg	High
98	F-35B	Opt2	Hot	Choppy	Mid	Far	High	Low	Med
99	F-35B	Opt2	Cold	Choppy	Mid	Near	Avg	High	Low
100	F-35B	Opt2	Cold	Choppy	Mid	Near	High	Avg	Med
101	AV-8B	Opt1	Hot	Rough	Mid	Avg	Avg	Low	Med
102	AV-8B	Opt1	Cold	Rough	Mid	Avg	Low	Avg	High
103	F-35B	Opt2	Hot	Choppy	Clear	Near	Low	Avg	High
104	F-35B	Opt2	Hot	Choppy	Mid	Avg	Low	Avg	Low

Sim Run #	Aircraft Type	Loadout	Temperature (F)	Sea State	Clouds	Ship2Shore Dist	Total Asset Qty	Assets per Launch	Threat
105	F-35B	Opt1	Avg	Calm	Clear	Near	Avg	High	High
106	F-35B	Opt2	Cold	Calm	Low	Far	Avg	Avg	Low
107	F-35B	Opt1	Hot	Rough	Low	Near	High	Avg	Low
108	AV-8B	Opt2	Hot	Rough	Clear	Far	Avg	Low	Med
109	F-35B	Opt2	Avg	Choppy	Mid	Near	Low	High	Med
110	F-35B	Opt2	Avg	Choppy	Low	Near	Avg	Avg	Med
111	F-35B	Opt1	Avg	Choppy	Clear	Far	Low	Low	Med
112	AV-8B	Opt1	Avg	Calm	Low	Near	Avg	Avg	Low
113	AV-8B	Opt1	Avg	Choppy	Clear	Avg	Low	Low	Low
114	AV-8B	Opt1	Cold	Choppy	Clear	Near	Low	Avg	Low
115	AV-8B	Opt2	Hot	Calm	Clear	Avg	Avg	High	Low
116	F-35B	Opt2	Hot	Choppy	Low	Avg	Avg	Low	High
117	AV-8B	Opt1	Avg	Rough	Low	Near	Low	High	Low
118	F-35B	Opt1	Avg	Calm	Mid	Far	High	High	Low
119	F-35B	Opt1	Hot	Calm	Low	Avg	Avg	High	High
120	AV-8B	Opt2	Avg	Choppy	Clear	Far	Avg	Avg	Low
121	AV-8B	Opt2	Cold	Rough	Low	Near	Avg	Low	Low
122	AV-8B	Opt1	Avg	Choppy	Mid	Far	High	Low	High
123	F-35B	Opt2	Cold	Calm	Low	Near	High	High	Low
124	AV-8B	Opt2	Hot	Rough	Low	Avg	High	High	Med
125	F-35B	Opt2	Avg	Rough	Low	Avg	Low	Low	Med
126	F-35B	Opt1	Avg	Rough	Mid	Near	Low	Avg	Low
127	F-35B	Opt1	Avg	Calm	Clear	Avg	Low	High	Low
128	AV-8B	Opt2	Avg	Calm	Low	Far	Avg	Low	High
129	F-35B	Opt1	Avg	Rough	Low	Near	Avg	Low	High
130	F-35B	Opt2	Cold	Calm	Mid	Avg	High	High	High
131	AV-8B	Opt1	Cold	Rough	Mid	Far	Low	High	Med

Sim Run #	Aircraft Type	Loadout	Temperature (F)	Sea State	Clouds	Ship2Shore Dist	Total Asset Qty	Assets per Launch	Threat
132	F-35B	Opt2	Avg	Choppy	Mid	Avg	High	Avg	High
133	F-35B	Opt2	Hot	Calm	Low	Avg	High	Avg	Med
134	F-35B	Opt1	Avg	Choppy	Low	Far	Avg	Avg	High
135	F-35B	Opt1	Hot	Choppy	Low	Far	Low	High	Med
136	AV-8B	Opt1	Hot	Choppy	Low	Far	Avg	High	Low

APPENDIX D. FACTOR VALUES USED FOR DOE STRATEGY

Custom Design DOE Strategy – GCS Ten Factors

Simulation Run #	Weapon Type	Transit Medium	Temperature	Sea State	Weapon Loadout	Ship2 Shore Dist	Shore 2Fire Pos Dist	Total Weapons Qty	Transit Med per Launch	Threat
1	M777A2	Air	Avg	Choppy	Prec	Near	High	Low	High	Med
2	M777A2	Sea	Avg	Choppy	Conv	Avg	Low	Avg	Avg	Med
3	EFSS	Sea	Avg	Choppy	Prec	Avg	Low	Low	High	Med
4	EFSS	Sea	Hot	Calm	Prec	Avg	High	Avg	Avg	Med
5	M777A2	Air	Cold	Choppy	Prec	Near	Low	Low	High	Low
6	M777A2	Sea	Cold	Rough	Prec	Far	Low	High	Avg	Med
7	EFSS	Sea	Cold	Calm	Prec	Avg	High	Low	High	High
8	EFSS	Air	Cold	Choppy	Conv	Avg	Avg	High	High	Low
9	Both	Sea	Hot	Choppy	Prec	Avg	Low	High	Avg	Med
10	M777A2	Sea	Hot	Rough	Conv	Avg	High	Low	High	Med
11	Both	Sea	Avg	Rough	Conv	Near	Low	High	Low	High
12	Both	Air	Hot	Choppy	Conv	Near	Avg	High	High	High
13	Both	Sea	Hot	Rough	Conv	Near	Avg	Low	High	High
14	M777A2	Air	Hot	Calm	Prec	Avg	High	Low	Low	Med
15	M777A2	Air	Avg	Calm	Conv	Avg	High	Low	High	Low
16	M777A2	Sea	Hot	Calm	Conv	Avg	Low	High	High	High
17	M777A2	Sea	Avg	Rough	Conv	Avg	Low	High	Low	Low
18	Both	Air	Avg	Choppy	Prec	Avg	High	High	Avg	High
19	Both	Air	Avg	Calm	Prec	Far	Low	Avg	Avg	Low

20	EFSS	Air	Hot	Rough	Prec	Avg	Avg	High	Avg	High
21	M777A2	Air	Avg	Rough	Conv	Near	Low	Low	Avg	Med
22	M777A2	Air	Hot	Rough	Prec	Near	Avg	High	High	Med
23	M777A2	Sea	Cold	Calm	Conv	Far	Low	Avg	Low	Low
24	EFSS	Air	Hot	Choppy	Prec	Avg	Avg	Low	Low	Low
25	M777A2	Sea	Hot	Rough	Prec	Near	Low	Low	Low	Med
26	EFSS	Sea	Avg	Calm	Conv	Far	Low	Avg	High	High
27	Both	Sea	Cold	Calm	Prec	Near	Avg	High	High	High
28	Both	Sea	Hot	Rough	Conv	Far	Low	Low	Low	High
29	Both	Sea	Cold	Rough	Conv	Avg	Avg	High	Avg	Med
30	Both	Sea	Hot	Rough	Prec	Far	High	Low	Avg	Low
31	EFSS	Sea	Cold	Rough	Prec	Far	Avg	Avg	High	Med
32	M777A2	Sea	Avg	Choppy	Prec	Near	Low	High	Avg	High
33	EFSS	Sea	Cold	Choppy	Prec	Near	High	Avg	Low	Med
34	Both	Air	Avg	Rough	Conv	Far	High	Avg	Avg	High
35	EFSS	Sea	Avg	Calm	Prec	Avg	Avg	High	Avg	Med
36	Both	Sea	Avg	Calm	Conv	Avg	High	Low	Avg	Med
37	EFSS	Air	Hot	Calm	Conv	Avg	High	Low	Avg	High
38	M777A2	Air	Avg	Rough	Prec	Far	High	High	Low	Med
39	EFSS	Air	Avg	Calm	Conv	Near	High	High	High	High
40	Both	Sea	Cold	Choppy	Conv	Near	High	Low	Low	High
41	EFSS	Sea	Cold	Choppy	Prec	Avg	High	Low	Avg	Low
42	Both	Air	Avg	Rough	Prec	Near	High	Avg	Low	Med
43	M777A2	Air	Avg	Calm	Conv	Far	Avg	High	High	Med
44	Both	Air	Hot	Rough	Conv	Avg	High	High	Low	Low
45	EFSS	Sea	Hot	Calm	Prec	Near	Avg	Avg	Low	High
46	Both	Air	Avg	Choppy	Conv	Near	Avg	Low	Low	Med
47	Both	Air	Cold	Rough	Conv	Near	High	High	High	Med

48	M777A2	Sea	Cold	Calm	Prec	Far	High	High	High	Low
49	Both	Sea	Avg	Rough	Prec	Avg	Avg	Low	Low	High
50	Both	Air	Avg	Rough	Prec	Near	Low	Low	Avg	Low
51	M777A2	Air	Hot	Calm	Conv	Far	High	Low	High	High
52	Both	Air	Avg	Rough	Conv	Avg	Avg	Avg	High	Low
53	Both	Sea	Avg	Choppy	Prec	Near	High	Avg	Avg	Med
54	M777A2	Sea	Avg	Choppy	Conv	Avg	Avg	Low	High	High
55	Both	Air	Avg	Choppy	Conv	Near	Low	Avg	High	High
56	EFSS	Sea	Avg	Choppy	Prec	Far	High	Low	Low	High
57	EFSS	Air	Avg	Rough	Conv	Far	Low	Low	High	High
58	EFSS	Air	Hot	Choppy	Prec	Near	Low	Avg	Low	Med
59	Both	Sea	Hot	Choppy	Conv	Far	High	Avg	Low	Med
60	M777A2	Air	Avg	Calm	Conv	Avg	High	Avg	Low	High
61	EFSS	Air	Hot	Calm	Conv	Far	Avg	Avg	Low	Low
62	EFSS	Air	Cold	Choppy	Conv	Far	High	High	Low	High
63	EFSS	Air	Hot	Rough	Prec	Near	Avg	Avg	Avg	Low
64	EFSS	Air	Cold	Choppy	Conv	Avg	Low	Avg	Avg	Low
65	Both	Sea	Cold	Rough	Prec	Near	High	High	Low	High
66	Both	Air	Hot	Calm	Prec	Avg	Avg	Low	Avg	Low
67	M777A2	Sea	Avg	Choppy	Prec	Avg	High	Low	Low	Low
68	M777A2	Sea	Avg	Calm	Conv	Far	High	High	Avg	High
69	Both	Air	Avg	Rough	Prec	Far	Avg	High	Avg	Low
70	M777A2	Air	Hot	Rough	Conv	Far	Low	High	High	Low
71	Both	Air	Hot	Calm	Conv	Near	Low	Low	High	Med
72	M777A2	Sea	Cold	Calm	Conv	Near	High	High	Low	Med
73	Both	Sea	Avg	Rough	Conv	Far	Low	Low	High	Med
74	EFSS	Sea	Hot	Choppy	Conv	Near	High	Low	High	Low
75	M777A2	Air	Cold	Calm	Prec	Avg	Low	High	Avg	Low

76	EFSS	Sea	Avg	Rough	Prec	Near	High	Low	Avg	Med
77	EFSS	Air	Avg	Choppy	Prec	Far	Low	High	High	High
78	EFSS	Sea	Cold	Rough	Conv	Avg	Low	Low	Avg	High
79	M777A2	Sea	Cold	Choppy	Prec	Avg	Low	Avg	Low	High
80	Both	Sea	Hot	Choppy	Prec	Near	Avg	Avg	Low	Low
81	EFSS	Sea	Cold	Choppy	Conv	Far	Low	Low	Low	Med
82	EFSS	Air	Avg	Rough	Prec	Near	Avg	Avg	High	High
83	M777A2	Air	Hot	Choppy	Prec	Far	Low	Low	Avg	High
84	M777A2	Air	Avg	Rough	Prec	Far	Avg	Low	High	Low
85	Both	Sea	Avg	Calm	Conv	Near	Avg	Avg	Avg	High
86	EFSS	Air	Avg	Choppy	Conv	Far	High	Avg	High	Med
87	Both	Sea	Cold	Calm	Conv	Near	High	High	Avg	Low
88	M777A2	Sea	Hot	Calm	Conv	Near	Low	Low	Avg	Low
89	M777A2	Sea	Cold	Calm	Prec	Avg	Avg	Low	Avg	Med
90	M777A2	Air	Cold	Rough	Prec	Avg	High	Low	Avg	High
91	Both	Air	Hot	Rough	Prec	Far	High	Avg	High	Med
92	EFSS	Air	Avg	Calm	Prec	Avg	Low	Low	Low	High
93	M777A2	Air	Cold	Calm	Conv	Far	High	Avg	Avg	Med
94	M777A2	Air	Cold	Rough	Prec	Avg	Low	Avg	High	Med
95	Both	Air	Hot	Rough	Prec	Avg	Low	Avg	Low	Low
96	Both	Sea	Cold	Calm	Prec	Avg	Low	Avg	Avg	High
97	EFSS	Air	Avg	Rough	Prec	Avg	High	High	High	Low
98	M777A2	Sea	Hot	Rough	Conv	Far	Avg	Avg	Avg	High
99	EFSS	Air	Cold	Rough	Conv	Avg	High	High	Avg	Med
100	EFSS	Sea	Hot	Calm	Conv	Avg	Avg	Low	Low	Med
101	M777A2	Air	Hot	Choppy	Prec	Avg	Avg	Avg	Avg	Med
102	M777A2	Sea	Hot	Choppy	Prec	Far	Avg	High	Low	Med
103	Both	Sea	Avg	Calm	Conv	Avg	Low	High	Low	Low

104	Both	Air	Cold	Choppy	Prec	Far	Avg	Low	High	Med
105	EFSS	Air	Hot	Rough	Prec	Far	High	Avg	Low	High
106	Both	Sea	Hot	Choppy	Prec	Avg	High	Low	High	High
107	M777A2	Air	Avg	Calm	Prec	Near	Avg	High	Low	Low
108	Both	Sea	Cold	Calm	Prec	Near	Low	Low	Low	Med
109	Both	Air	Avg	Calm	Prec	Far	High	High	Low	High
110	EFSS	Air	Avg	Choppy	Conv	Near	Low	High	Avg	Low
111	M777A2	Sea	Hot	Choppy	Conv	Avg	Avg	High	Avg	Low
112	M777A2	Sea	Avg	Calm	Prec	Far	Avg	Avg	Low	Med
113	EFSS	Sea	Avg	Choppy	Conv	Avg	High	High	Low	High
114	M777A2	Sea	Cold	Rough	Prec	Near	High	Avg	High	Low
115	Both	Sea	Hot	Choppy	Conv	Avg	Avg	Avg	High	Med
116	M777A2	Air	Cold	Calm	Prec	Near	Low	Avg	Avg	High
117	Both	Air	Cold	Rough	Conv	Near	Low	Avg	Low	Low
118	EFSS	Air	Hot	Rough	Conv	Avg	Low	High	Low	Med
119	EFSS	Air	Cold	Choppy	Prec	Near	Low	Low	High	High
120	M777A2	Air	Hot	Rough	Conv	Near	High	Low	Low	High
121	EFSS	Air	Avg	Rough	Conv	Avg	Avg	Low	Avg	Low
122	M777A2	Sea	Cold	Rough	Prec	Far	Low	Low	High	High
123	M777A2	Air	Hot	Calm	Prec	Near	High	High	Avg	Med
124	EFSS	Air	Avg	Calm	Prec	Far	Avg	Low	Avg	High
125	EFSS	Air	Hot	Calm	Prec	Avg	Low	High	High	Low
126	EFSS	Air	Hot	Choppy	Prec	Far	High	High	Avg	Low
127	M777A2	Sea	Avg	Choppy	Conv	Near	Avg	Avg	High	Low
128	Both	Sea	Cold	Calm	Conv	Far	Low	Avg	High	Low
129	EFSS	Sea	Cold	Rough	Conv	Far	High	Low	Avg	Low
130	M777A2	Air	Cold	Rough	Conv	Avg	Avg	Avg	Low	Med
131	Both	Sea	Avg	Choppy	Conv	Far	Avg	High	High	High

132	Both	Air	Avg	Rough	Conv	Far	High	Low	Low	Low
133	Both	Air	Cold	Calm	Conv	Avg	Low	Avg	Low	Med
134	Both	Sea	Avg	Rough	Prec	Avg	High	Avg	High	High
135	EFSS	Sea	Avg	Calm	Conv	Near	Low	Avg	Low	Med
136	M777A2	Air	Cold	Calm	Conv	Avg	Avg	Avg	High	High
137	M777A2	Sea	Avg	Choppy	Conv	Far	Low	Low	Avg	Low
138	Both	Sea	Hot	Calm	Prec	Far	Avg	High	Avg	High
139	EFSS	Sea	Cold	Rough	Conv	Near	Avg	Avg	Avg	High
140	Both	Sea	Cold	Calm	Conv	Far	Avg	Low	Low	Low
141	Both	Air	Avg	Calm	Prec	Near	Low	High	High	Med
142	EFSS	Sea	Hot	Choppy	Conv	Far	Avg	Avg	Avg	Med
143	EFSS	Sea	Avg	Calm	Prec	Near	Avg	Low	High	Low
144	M777A2	Sea	Cold	Rough	Prec	Near	Avg	Low	Low	Low
145	Both	Air	Cold	Choppy	Conv	Near	Low	High	Avg	Med
146	M777A2	Air	Cold	Choppy	Conv	Near	Avg	Low	Avg	Low
147	EFSS	Air	Cold	Calm	Prec	Avg	High	Avg	Low	Low
148	EFSS	Sea	Hot	Calm	Conv	Far	High	High	High	Med
149	EFSS	Sea	Avg	Rough	Prec	Far	Low	Avg	Low	Low
150	EFSS	Air	Cold	Calm	Prec	Far	Avg	High	Low	Med
151	M777A2	Sea	Avg	Rough	Conv	Near	High	Avg	Avg	Low
152	Both	Sea	Hot	Calm	Conv	Near	High	Avg	High	Low
153	EFSS	Sea	Hot	Calm	Prec	Far	Low	Low	Avg	Med
154	Both	Air	Hot	Choppy	Conv	Avg	High	Avg	Avg	Low
155	M777A2	Sea	Cold	Choppy	Conv	Avg	High	High	High	Med
156	Both	Air	Hot	Rough	Conv	Far	Avg	Low	Low	Med
157	M777A2	Sea	Hot	Choppy	Prec	Far	Low	Avg	High	Low
158	Both	Air	Cold	Calm	Conv	Far	Low	Low	Avg	High
159	Both	Air	Cold	Rough	Conv	Avg	Low	High	High	High

160	Both	Sea	Cold	Rough	Prec	Avg	High	Low	High	Low
161	Both	Sea	Hot	Rough	Conv	Near	Low	Avg	Avg	Med
162	EFSS	Sea	Hot	Rough	Conv	Near	Avg	High	Low	Low
163	Both	Sea	Cold	Choppy	Prec	Far	Low	High	Low	Low
164	M777A2	Air	Cold	Choppy	Prec	Far	Avg	Avg	Low	High
165	EFSS	Sea	Hot	Rough	Conv	Avg	Low	Avg	High	Low
166	EFSS	Sea	Cold	Rough	Prec	Near	Low	High	High	Low
167	EFSS	Air	Cold	Calm	Conv	Near	Avg	Low	High	Med
168	M777A2	Sea	Hot	Choppy	Conv	Near	High	Avg	Avg	High
169	M777A2	Sea	Hot	Rough	Prec	Avg	Avg	High	High	Low
170	M777A2	Air	Hot	Choppy	Conv	Avg	Low	Low	Low	Med

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APPENDIX E. ANALYSIS OF MOPS USING THE METAMODELS

A. CAS ANALYSIS

For each metamodel developed, an analysis was conducted in order to a) identify which metamodel factor or factor interaction had the largest impact on each MOP, b) identify the most significant interactions between MOPs, and c) identify the best combination of fuel usage and operational effectiveness in terms of the MOPs identified.

1. CAS #1 Metamodel Total Fuel Used Analysis

For the CAS #1 Metamodel *Total Fuel Used,* the top ten model factors or factor interactions that had the largest impact are shown in Table 58. As shown, the factor Ship2Shore Dist when at the (far) distance of 300 NM, had the largest effect of increasing the total fuel used during the MEU operation. This was followed closely by the factor Total Asset Qty at the (high) value of 115% of current doctrine, which had the 2nd largest effect of increasing the total fuel used during the MEU operation. The factor Total Asset Qty at the (low) value of 80% of current doctrine had the largest effect of decreasing the total fuel used during the MEU operation. In addition, the factor Ship2Shore Dist when at the (near) distance of 60 NM had the 2nd largest effect of decreasing the total fuel used during the MEU operation. The interaction between the factor Ship2Shore Dist at the (far) value and the factor Total Asset Qty at the (low) value suggest that if operating at the far distance of 300 NM, total fuel used could be reduced by operating with the Total Asset Qty at the (low) value of 80% of current doctrine.

Table 58. CAS #1 Metamodel *Total Fuel Used* Ten Most Significant Factor Effects

Factor or Factor Interaction	Metamodel Coefficient Value	Effect
Ship2Shore Dist[Far]	22,761.1	(+) Increases Fuel Used
Total Asset Qty[High]	19,450.8	(+) Increases Fuel Used
Total Asset Qty[Low]	-18,889.4	(-) Decreases Fuel Used
Ship2Shore Dist[Near]	-14,096.4	(-) Decreases Fuel Used
Ship2Shore Dist[Far]*Total Asset Qty[Low]	-10,338.2	(-) Decreases Fuel Used
Ship2Shore Dist[Far]*Total Asset Qty[High]	9,981.3	(+) Increases Fuel Used
Ship2Shore Dist[Avg]	-8,664.8	(-) Decreases Fuel Used
Total Asset Qty[High]*Assets per Launch[High]	-7,403.3	(-) Decreases Fuel Used
Ship2Shore Dist[Near]*Total Asset Qty[Low]	6,497.3	(+) Increases Fuel Used
Ship2Shore Dist[Near]*Total Asset Qty[High]	-6,131.2	(-) Decreases Fuel Used

2. CAS #3 Metamodel Average Mission Time Analysis

For the CAS #3 Metamodel *Average Mission Time*, the top ten model factors or factor interactions that had the largest impact on this average are shown in Table 59. As shown, the factor Assets per Launch when at the (high) value of 150% of current doctrine, had the largest effect of decreasing the average mission time of the MEU operation. This was followed very closely by the factor Assets per Launch when at the (low) value of 50% of current doctrine, which had the largest effect of increasing the average mission time of the MEU operation. The factor Total Asset Qty at the (low) value of 80% of current doctrine, the factor Threat at the (low) threat value, and the weather factor Clouds at the (low) value of overcast (< 5000 ft elevation) all had a similar effect of decreasing the average mission time of the MEU operation. The interaction between the factor Loadout at the (Opt2) value and the factor Clouds at the (clear) value suggested that operating with the clouds at an elevation >25,000 feet allowed the aircraft

to take advantage of their full complement of weapons (Opt2), thus reducing the average mission time needed to defeat the enemy.

Table 59. CAS #3 Metamodel *Average Mission Time* Ten Most Significant Factor Effects

Factor or Factor Interaction	Metamodel Coefficient Value	Effect
Assets per Launch[High]	-35. 8	(-) Decreases Mission Time
Assets per Launch[Low]	35.4	(+) Increases Mission Time
Total Asset Qty[Low]	-23.9	(-) Decreases Mission Time
Threat[Low]	-23.9	(-) Decreases Mission Time
Clouds[Low]	-23.8	(-) Decreases Mission Time
Loadout[Opt2]	23.6	(+) Increases Mission Time
Loadout[Opt1]	-23.7	(-) Decreases Mission Time
Threat[High]	18.5	(+) Increases Mission Time
Loadout[Opt1]*Clouds[Clear]	14.1	(+) Increases Mission Time
Loadout[Opt2]*Clouds[Clear]	-14.1	(-) Decreases Mission Time

3. CAS #4 Metamodel Targets Neutralized Analysis

For the CAS #4 Metamodel *Targets Neutralized*, the top ten model factors or factor interactions that had the largest impact on this average are shown in Table 60. As shown, no single factor had an effect that was in the top ten, only factor interactions. The factor interaction between the factor Sea State at the (rough) value and the factor Assets per Launch at the (low) value suggested that the operational limitations imposed by a (Rough) value of >8 foot waves and Assets per Launch at a (low) value of <50% current doctrine, had the largest effect of reducing the average percentage of targets neutralized. A similar negative effect on percentage of targets neutralized was shown by the interaction of the factor Temperature at the (hot) value and the factor Threat at the (high) threat value. In this case, the weather value of 80 (degrees F), impacted fuel burn rates and coupled with the factor Threat at the (high) threat value, combined to have a negative effect on the average percentage of targets neutralized. However, the interaction between the factor Clouds at the (mid) value and the factor Total Asset Qty at the (high) value

suggested that operations with Clouds at the (mid) value of 5,000 to 25,000 foot elevation combined with the factor Total Asset Qty at the (high) value of 115% of current doctrine, resulted in a positive effect on increasing the average percentage of targets neutralized during the MEU operation.

Table 60. CAS #4 Metamodel *Targets Neutralized* Ten Most Significant Factor Effects

Factor or Factor Interaction	Metamodel Coefficient Value	Effect
Sea State[Rough]*Assets per Launch[Low]	-8.6	(-) Decreases Targets Neutralized
Clouds[Mid]*Total Asset Qty[High]	8.5	(+) Increases Targets Neutralized
Temperature[Hot]*Threat[High]	-8.0	(-) Decreases Targets Neutralized
Aircraft Type[F-35B]*Clouds[Mid]	-4.5	(-) Decreases Targets Neutralized
Ship2Shore Dist[Near]*Assets per Launch[Avg]	-4.4	(-) Decreases Targets Neutralized
Clouds[Mid]*Threat[Low]	4.4	(+) Increases Targets Neutralized
Total Asset Qty[Avg]*Threat[Med]	4.3	(+) Increases Targets Neutralized
Clouds[Low]*Threat[Med]	4.2	(+) Increases Targets Neutralized
Ship2Shore Dist[Near]*Assets per Launch[Low]	4.2	(+) Increases Targets Neutralized
Temperature[Hot]*Ship2Shore Dist[Near]	-4.2	(-) Decreases Targets Neutralized

4. CAS #6 Metamodel Blue Casualty Analysis

For the CAS #6 Metamodel *Blue Casualty*, the top ten model factors or factor interactions that had the largest impact on this average are shown in Table 61. As shown, the factor Total Asset Qty at the (Low) value was the only single factor in the top ten that effected the average number of blue force assets destroyed during the MEU operation. This suggested that the factor Total Asset Qty at the (low) value of <80% of current

doctrine, resulted in a positive effect on increasing the average number of blue force assets destroyed during the MEU operation. The factor interaction between the factor Clouds at the (low) value and the factor Threat at the (high) threat value suggested that the operational limitations imposed by clouds at the low elevation of <5000 feet combined with a high Threat, had a significant effect on increasing the average number of blue force assets destroyed during the MEU operation. However, if operational limitations due to weather were relaxed, as shown by the factor Clouds at the (mid) value of > 5000 to < 25,000 feet elevation combined with the same (high) threat factor, the effect was to reduce the average number of blue force assets destroyed during the MEU.

Table 61. CAS #6 Metamodel *Blue Casualty* Ten Most Significant Factor Effects

Factor or Factor Interaction	Metamodel Coefficient Value	Effect
Clouds[Low]*Threat[High]	3.4	(+) Increases Blue Force Assets Destroyed
Clouds[Low]*Threat[Med]	-2.2	(-) Decreases Blue Force Assets Destroyed
Clouds[Mid]*Threat[High]	-2.2	(-) Decreases Blue Force Assets Destroyed
Total Asset Qty[Low]*Threat[High]	2.1	(+) Increases Blue Force Assets Destroyed
Total Asset Qty[Low]	2.1	(+) Increases Blue Force Assets Destroyed
Total Asset Qty[Low]*Threat[Low]	-2.1	(-) Decreases Blue Force Assets Destroyed
Temperature[Hot]*Ship2Shore Dist[Far]	1.5	(+) Increases Blue Force Assets Destroyed
Temperature[Avg]*Assets per Launch[Low]	1.4	(+) Increases Blue Force Assets Destroyed
Ship2Shore Dist[Near]*Assets per Launch[Low]	1.3	(+) Increases Blue Force Assets Destroyed
Clouds[Clear]*Threat[Med]	1.3	(+) Increases Blue Force Assets Destroyed

5. CAS #9 Metamodel Mission Success Analysis

For the CAS #9 Metamodel *Mission Success*, the top ten model factors or factor interactions that had the largest impact on this average are shown in Table 62. As shown, the interaction of factor Total Asset Qty at the (low) value of 80% of current doctrine and the factor Threat at the (high) threat value had the largest effect of decreasing mission

success of the MEU operation. The interaction of the factor Total Asset Qty at the (low) value of 80% of current doctrine and the factor Threat at the (low) threat value had the largest effect of increasing mission success of the MEU.

Table 62. CAS #9 Metamodel *Mission Success* Ten Most Significant Factor Effects

Factor or Factor Interaction	Metamodel Coefficient Value	Effect
Total Asset Qty[Low]*Threat[High]	-0.113	(-) Decreases Mission Success
Total Asset Qty[Low]*Threat[Low]	0.105	(+) Increases Mission Success
Clouds[Low]*Threat[High]	-0.096	(-) Decreases Mission Success
Total Asset Qty[Low]	-0.082	(-) Decreases Mission Success
Threat[Low]	0.082	(+) Increases Mission Success
Total Asset Qty[Avg]*Threat[High]	0.076	(+) Increases Mission Success
Threat[High]	-0.075	(-) Decreases Mission Success
Clouds[Mid]*Threat[High]	0.067	(+) Increases Mission Success
Sea State[Rough]*Assets per Launch[Low]	0.067	(+) Increases Mission Success
Total Asset Qty[Avg]*Threat[Low]	-0.066	(-) Decreases Mission Success

B. GCS ANALYSIS

For each metamodel developed, an analysis was conducted in order to a) identify which metamodel factor or factor interaction had the largest impact its respective MOP, b) identify the most significant interactions between MOPs, and c) identify the best combination of fuel usage and operational effectiveness in terms of the MOPs identified.

1. GCS #1 Metamodel Total Fuel Used Analysis

For the GCS #1 Metamodel *Total Fuel Used*, the top ten model factors or factor interactions that had the largest impact on this average are shown in Table 63. As shown, the factors Transit Medium when (air) and Transit Medium when (sea), both had the largest effect on total fuel used during the MEU operation. This was followed closely by the factor Total Weapons Qty at the (high) value of (6 Howitzers / 8 EFSS), which had the second largest effect of increasing the total fuel used during the MEU operation. In

addition, the factor Total Weapons Qty at the (low) value of (2 Howitzers / 2 EFSS) had the second largest effect of decreasing the total fuel used during the MEU operation.

Table 63. GCS #1 Metamodel *Total Fuel Used* Ten Most Significant Factor Effects

Factor or Factor Interaction	Metamodel Coefficient Value	Effect
Transit_Medium[Air]	9,978.5	(+) Increases Fuel Used
Transit_Medium[Sea]	-9,978.5	(-) Decreases Fuel Used
Total_Weapons_Qty[High]	7,975.4	(+) Increases Fuel Used
Ship2Shore_Dist[Far]	7,738.7	(+) Increases Fuel Used
Ship2Shore_Dist[Near]	-7,272.6	(-) Decreases Fuel Used
Total_Weapons_Qty[Low]	-7,058.6	(-) Decreases Fuel Used
Weapon_Type[Both]	6,800.1	(+) Increases Fuel Used
Weapon_Type[M777A2]*Transit_Medium[Air]	-5,221.8	(-) Decreases Fuel Used
Weapon_Type[M777A2]*Transit_Medium[Sea]	5,221.8	(+) Increases Fuel Used
Transit_Medium[Air]*Total_Weapons_Qty[High]	5,171.4	(+) Increases Fuel Used

2. GCS #6 Metamodel Average Mission Time Analysis

For the GCS #6 Metamodel *Average Mission Time*, the top ten model factors or factor interactions that had the largest impact on this average are shown in Table 64. As shown, the factor Ship2ShoreDist when at the (far) value of 150 NM, had the largest effect of increasing the average mission time of the MEU operation. This was followed by the factor Total Weapons Qty at the (high) value of (6 Howitzers / 8 EFSS) weapons, which also had the effect of increasing mission time. The factor Ship2ShoreDist when at the (near) value of 10 NM, had the largest effect of decreasing the average mission time of the MEU operation.

Table 64. GCS #6 Metamodel *Average Mission Time* Ten Most Significant Factor Effects

Factor or Factor Interaction	Metamodel Coefficient Value	Effect
Ship2Shore_Dist[Far]	365.5	(+) Increases Mission Time
Ship2Shore_Dist[Near]	-289.1	(-) Decreases Mission Time
Total_Weapons_Qty[High]	264.7	(+) Increases Mission Time
Ship2Shore_Dist[Far]*Total_Weapons_Qty[High]	219.1	(+) Increases Mission Time
Total_Weapons_Qty[High]*Transit_Med_per_Launch[High]	-209.0	(-) Decreases Mission Time
Total_Weapons_Qty[Low]	-206.7	(-) Decreases Mission Time
Transit_Med_per_Launch[Low]	188.4	(+) Increases Mission Time
Ship2Shore_Dist[Near]*Transit_Med_per_Launch[Low]	-186.6	(-) Decreases Mission Time
Ship2Shore_Dist[Near]*Total_Weapons_Qty[High]	-186.2	(-) Decreases Mission Time
Ship2Shore_Dist[Far]*Transit_Med_per_Launch[Low]	182.0	(+) Increases Mission Time

3. GCS #7 Metamodel Targets Neutralized Analysis

For the GCS #7 Metamodel *Targets Neutralized*, the top ten model factors or factor interactions that had the largest impact on this average are shown in Table 65. As shown, the factor Threat at the (low) threat value had the largest effect of increasing the percentage of targets neutralized during the MEU operation. The interaction between the factor Total Weapons Qty at the (low) value of (2 Howitzers / 2 EFSS) and the factor Threat at the (low) threat value had the largest effect of decreasing the percentage of targets neutralized. A comparable effect of reducing the percentage of targets neutralized was produced by the factor Threat at the (Med) threat value.

Table 65. GCS #7 Metamodel *Targets Neutralized* Ten Most Significant Factor Effects

Factor or Factor Interaction	Metamodel Coefficient Value	Effect
Threat[High]	-26.48	(-) Decreases Targets Neutralized
Threat[Low]	26.47	(+) Increases Targets Neutralized
Total_Weapons_Qty[Low]	-24.65	(-) Decreases Targets Neutralized
Total_Weapons_Qty[High]	22.64	(+) Increases Targets Neutralized
Weapon_Type[Both]	13.71	(+) Increases Targets Neutralized
Weapon_Type[EFSS]	-13.00	(-) Decreases Targets Neutralized
Total_Weapons_Qty[Low]*Threat[High]	11.16	(+) Increases Targets Neutralized
Total_Weapons_Qty[High]*Threat[High]	-10.46	(-) Decreases Targets Neutralized
Weapon_Type[Both]*Threat[High]	-10.28	(+) Increases Targets Neutralized
Weapon_Type[EFSS]*Threat[High]	10.03	(+) Increases Targets Neutralized

4. GCS #8 Metamodel Blue Casualty Analysis

For the GCS #8 Metamodel *Blue Casualty*, the top ten model factors or factor interactions that had the largest impact on this average are shown in Table 66. As shown, the factor Threat at the (low) threat value had the largest effect of decreasing the percentage of blue force assets destroyed. On the other hand, the factor Threat at the (high) threat value had the largest effect of increasing the percentage of blue force assets destroyed. The interaction between the factor Weapon Type at the (EFSS) value and the factor Transit Medium at the (sea) value significantly decreased the percentage of blue force assets destroyed. The interaction between the factor Weapon Type at the (EFSS) value and the factor Transit Medium at the (air) value had an equal, but opposite effect of increasing the percentage of blue force assets destroyed during the MEU operation.

Table 66. GCS #8 Metamodel *Blue Casualty* Ten Most Significant Factor Effects

Factor or Factor Interaction	Metamodel Coefficient Value	Effect
Threat[Low]	-26.27	(-) Decreases Blue Force Assets Destroyed
Threat[High]	20.46	(+) Increases Blue Force Assets Destroyed
Total_Weapons_Qty[Low]	20.31	(+) Increases Blue Force Assets Destroyed
Total_Weapons_Qty[High]	-18.04	(-) Decreases Blue Force Assets Destroyed
Weapon_Type[EFSS]*Transit_Medium[Air]	11.87	(+) Increases Blue Force Assets Destroyed
Weapon_Type[EFSS]*Transit_Medium[Sea]	-11.87	(-) Decreases Blue Force Assets Destroyed
Weapon_Type[M777A2]*Transit_Medium[Air]	-11.47	(-) Decreases Blue Force Assets Destroyed
Weapon_Type[M777A2]*Transit_Medium[Sea]	11.47	(+) Increases Blue Force Assets Destroyed
Transit_Medium[Air]	-9.01	(-) Decreases Blue Force Assets Destroyed
Transit_Medium[Sea]	9.01	(+) Increases Blue Force Assets Destroyed

5. GCS #10 Metamodel Mission Success Analysis

For the GCS #10 Metamodel *Mission Success*, the top ten model factors or factor interactions that had the largest impact on this average are shown in Table 67. As shown, the factor Threat at the (low) threat value and the factor Threat at the (high) threat value had the largest effect of increasing / decreasing mission success. The interaction of the factor Total Weapons Qty at the (high) value of 150% of doctrine interacting with the factor Threat at the (low) and (high) threat values had the second largest effect of increasing / decreasing mission success.

Table 67. GCS #10 Metamodel *Mission Success* Ten Most Significant Factor Effects

Factor or Factor Interaction	Metamodel Coefficient Value	Effect
Total_Weapons_Qty[Low]	-0.1986	(-) Increases Mission Success
Threat[Low]	0.1901	(+) Decreases Mission Success
Threat[High]	-0.1808	(-) Increases Mission Success
Total_Weapons_Qty[High]*Threat[High]	0.1497	(+) Decreases Mission Success
Total_Weapons_Qty[High]*Threat[Low]	-0.1496	(-) Decreases Mission Success
Total_Weapons_Qty[Low]*Threat[High]	-0.1345	(-) Decreases Mission Success
Weapon_Type[M777A2]*Transit_Medium[Air]	0.1122	(+) Increases Mission Success
Weapon_Type[M777A2]*Transit_Medium[Sea]	-0.1122	(-) Decreases Mission Success
Total_Weapons_Qty[Low]*Threat[Low]	0.1043	(+) Decreases Mission Success
Temperature[Avg]*Transit_Med_per_Launch[High]	-0.1041	(-) Decreases Mission Success

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